Before the
FEDERAL COMMUNICATIONS COMMISSION
Washington, D.C. 20554

In the Matter of	**)**	
Establishment of an Improved Model for	**)**	
Predicting the Broadcast Television Field	**)**	**ET Docket No. 00-11**
Strength Received at Individual Locations	**)**	

IN RESPONSE TO NOTICE OF PROPOSED RULEMAKING
Comments of Richard L. Biby, PE

Introduction

In the instant proceeding (NRPM ET 00-11), the Federal Communications Commission ("FCC" or "the Commission") proposes rules prescribing a point-to-point predictive model for determining the ability of individual locations to receive an over-the-air television broadcast signal of a specific intensity through the use of a conventional, stationary, outdoor rooftop receiving antenna. The stated goal in developing this model is to provide a means for reliably and presumptively determining whether the over-the-air signals of network affiliated television stations can be received at individual locations. Satellite carriers use such determinations in establishing the eligibility of individual households to receive the signals of television broadcast network stations via their satellite-to-home service. In issuing this proposal, the FCC is complying with new statutory requirements set forth in the Satellite Home Viewer Improvement Act of 1999 (SHVIA). The signal intensity for determining eligibility is the Grade B standard set forth in §73.683(a) of the Commission's rules (47 CFR, Part 73).

Regarding the Commenter

These comments are being offered because I believe that my background of experience, which is a matter of record at the FCC, has applicability to the discussion at hand. I have received no remuneration whatsoever for this effort. My comments are in the first-person-singular to emphasize the fact that these are my personal opinions, unbiased by third-party concerns.

It is stated for the record that I have no present relationship with any business entity in either the broadcast television or satellite carrier industries. However, I did testify in United States District Court, Southern District of Florida, Miami Division in *Case No. 96-3650-CIV-Nesbitt, CBS Inc., Et Al, Plaintiffs, V. Primetime 24 Joint Venture, Et Al, Defendants.*

My testimony, on behalf of the defendants in the above case, was limited to a critique of signal coverage maps that had been prepared on behalf of the plaintiffs.

Certain commercial products are mentioned in these comments for the sole purpose of illustrating the ready availability of equipment capable of performing desired functions. No endorsement of those products is intended.

Scope of Instant Rule Making

As is stated in NRPM ET 00-11:

> The SHVIA revises and extends statutory provisions established by Congress in the 1988 Satellite Home Viewer Act (SHVA). With regard to prediction of signal availability, the SHVIA adds a new section 339(c)(3) to the Communications Act of 1934, as amended (47 U.S.C.), which requires that "[W]ithin 180 days after the date of enactment of the Satellite Home Viewer Improvement Act of 1999, the Commission shall take all actions necessary, including any reconsideration, to develop and prescribe by rule a point-to-point predictive model for reliably and presumptively determining the ability of individual locations to receive signals in accordance with the signal intensity standard in effect under section 119(d)(10)(A) of title 17, United States Code." Section 339(c)(3) further provides that "[I]n prescribing such a model, the Commission shall rely on the Individual Location Longley-Rice model set forth by the Federal Communications Commission in Docket No. 98-201, and ensure that such model takes into account terrain, building structures, and other land cover variations. The Commission shall establish procedures for the continued refinement in the application of the model by the use of additional data as it becomes available." The SHVIA also requires that the courts rely on the Individual Location Longley Rice model established by the Commission for making presumptive determinations of whether a household is capable of receiving broadcast television signals of Grade B intensity.
>
> In its *Report and Order* in CS Docket No. 98-201 (*SHVA Report and Order*), the Commission endorsed the use of a specific model for predicting signal strength at individual locations. This model, which the Commission termed "Individual Location Longley-Rice" or "ILLR," is a version of Longley-Rice 1.2.2. The Commission recommended that the ILLR model be used for determining a presumption of service or lack of service by local over-the-air television signals at individual locations for purposes of establishing a household's eligibility to receive network television programming by satellite carriers under the SHVA.

The Satellite Home Viewer Improvement Act Test of "Unserved Household"

In the Satellite Home Viewer Act (SHVA), Congress granted a limited exception to the programming copyrights of television networks and their affiliate stations that allows reception of network programming via direct-to-home (DTH) satellite service "to persons who reside in unserved households." For purposes of the instant proceeding, the term "unserved household" is defined by SHVIA to mean a household that --

> Cannot receive, through the use of a conventional, stationary, outdoor rooftop receiving antenna, an over-the-air signal of a primary network station affiliated with that network of Grade B intensity as defined by the Federal Communications Commission under Section 73.683(a) of title 47 of the Code of Federal regulations, as in effect on January 1, 1999;

A Note Regarding Television Reception Terminology

In the case at hand, *intensity* refers to signal strength, described in terms of Volts (or micro-Volts) per meter. An *antenna* is a device that transforms the energy in a passing radio wave into a *voltage*, which, when applied to a *transmission line*, causes a *current* to flow in the transmission line.

The transmission line is connected to a *receiver*. According to Merriam Webster's Collegiate Dictionary, a receiver is: "1 d: a device for converting signals (as electromagnetic waves) into audio or visual form; as (1): a device in a telephone for converting electrical impulses or varying current into sound (2): a radio receiver with a tuner and an amplifier on one chassis".

Provided that the *receiver*, *transmission line*, and *antenna* are all properly matched (that is, designed so as to work correctly with one another) the received signal *power* will be transferred to the receiver with a minimum of decrease in its strength (*attenuation*).

Unfortunately, the receiver itself can never be perfect; it creates internal set noise, which appears on the picture screen as "snow" and there may be other noise, received by the antenna and delivered to the receiver, due largely to electrical appliances in the neighborhood ("urban noise" or "man-made noise"). Finally, other television stations may create objectionable *co- or adjacent-channel* interference.

SHVIA Definition of "Unserved Household" Parsed to Plain English

The impact of SHVIA's definition of "unserved household" has been the subject of much discussion. It seems reasonable that parsing that paragraph into plain English would be a good approach toward understanding its essence. Meanings of individual words of particular importance as found in Merriam Webster's Collegiate Dictionary, Tenth Edition, are quoted, below. (Obvious meanings of certain words are not in quotes.)

> Cannot – (negation of auxiliary verb) implies inability, not a lack of desire, to accomplish something. In context, there may be many reasons why a given householder *cannot* receive a television signal; the residence may be in a high-rise building where rooftop antennas are not allowed, or there may be zoning ordinances against such antennas.
>
> Receive – (intransitive verb) " 3: to convert incoming radio waves into *perceptible* signals"
>
> Perceptible – (adjective) ": capable of being perceived, especially by the senses <a perceptible change in her tone><the light became increasingly perceptible>
>
> Conventional – (adjective) " 2 b: lacking originality or individuality: trite c (1): ordinary; commonplace"
>
> Stationary – (adjective) " 1: fixed in a station, course, or mode: immobile"
>
> Antenna – (noun) " 2: a usually metallic device (as a rod or wire) for radiating or receiving radio waves"
>
> Conventional outdoor rooftop receiving antenna – The FCC made certain assumptions regarding receive antenna performance ("gain") in the derivation of numerical values of Grade A and Grade B signal strengths. Specifically, the assumed gains were 6 dBd (deciBbels relative to a half-wave dipole) at VHF and 13 dBd at UHF. There is an antenna engineering rule-of-thumb that the gain of an antenna increases about 3 dB for each doubling of the number of elements, which would indicate about a four-element antenna at VHF and perhaps bow-tie antennas in front of a screen, stacked about four high at UHF. These are not simple antennas. An additional 3.0 dB or so increase in required gain would result in much larger (about twice as big), more expensive antennas than the average householder is likely to want to deal with. Further, the difficulty of measuring (and characterizing the variability of) signal strength at a given location makes it difficult to ensure an accuracy of better than 3.0 dB or so. In

summary, feasible increases in antenna performance are not a significant factor in this proceeding.

Over-the-air can reasonably be taken in context to mean not via cable.

Primary network station has been defined in SHVIA to mean the main transmission facility of a network affiliate station, and not translators or Satellite TV stations.

Signal – (noun) " 4 b: the sound or image conveyed in telegraphy, radio, radar, or television; c: a detectable physical quantity or impulse (as a voltage, current, or magnetic field strength) by which messages or information can be transmitted"

Intensity – (noun) " 2: the magnitude of a quantity (as force or energy) per unit (as of area, charge, mass, or time)"

The SHVIA Unserved Household Test, As Translated

Thus, SHVIA's reference to Grade B intensity immediately qualifies as unserved those households in locations where the actual signal strength of network affiliate station(s) is less than that specified in Section 73.683 of the FCC Rules. Nowhere does SHVIA even mention a measurement of signal strength."

Further, SHVIA's reference to the Grade B standard, the development of which flows from the requirement that the received picture be acceptable to the median viewer, qualifies as unserved those households, regardless of signal strength, that cannot receive an acceptable picture.

FCC Definition of Grade A and Grade B Signal Strength Contours

The FCC specifies minimum required field strength values for two service contours, Grade A and Grade B, with the further requirement that a certain predicted signal strength ("City Grade") encompass the principal community to be served. The required field strength for each of these contours is ultimately based on received picture quality and the probability of successful reception at any given location. That picture quality, which seems unlikely to be acceptable in today's environment, was only marginally acceptable to half of the observers who participated in the extensive viewer satisfaction testing performed by the Television Allocations Study Organization (TASO) during the late 1950's. TASO developed a six-level picture quality rating system, from Grade One ("Excellent – The picture is of extremely high quality, as good as you could desire.") through Grade Three ("Marginal – The picture is of acceptable quality. Interference is not objectionable.") to Grade 6 ("Unusable – The picture is so bad that you could not watch It.").

The FCC based its channel allotment planning factors on a signal to noise ratio of 30.0 dB, which corresponds closely to TASO Grade 3 (See Development of Grade B Planning Factors, herein). Keeping in mind that Grade 3 corresponds to a picture that was only barely acceptable to half the viewers almost four decades ago, before there was much of a television presence in this country, it would seem unlikely that a picture of that quality would be acceptable today. It is suggested that a TASO Grade 2 picture ("Fine – The picture is of high quality providing enjoyable viewing. Interference is perceptible.") might be a more appropriate present day goal. TASO Grade 2 represents a signal-to-noise ratio of about 36.0 dB.

Development of Grade B Planning Factors

The actual values assumed by the FCC for various important parameters in their derivation of the values for Grade B were discussed in "*Understanding Television's Grade A and Grade B Service Contours'*, by R. A. O'Connor (IEEE Transactions on Broadcasting, Volume BC-14, Number 4, December 1968). The derivation of the Grade B values is as follows:

Parameter	Unit	Sign	Channels 2 to 6	Channels 7 to 13	Channels 14 to 83
Nt	dBu	+	7	7	7
Ns	dB	+	12	12	15
Snr	dB	+	30	30	30
Kd	dB	-	3	-6	-16
G	dB	-	6	6	13
L	dB	+	1	2	5
ΔT 90%	dB	+	6	5	4
ΔL	dB	+	0	0	0
Grade B Values	dBu		47	56	64

Where:

Nt is the inherent thermal noise generated across the terminals of an ideal receiver. Thermal noise is a function of temperature, bandwidth, and circuit resistance. Assuming 300-Ohm input impedance for a TV receiver having a bandwidth of 4.0 MHz and room temperature (290 Degrees, Kelvin), thermal noise is 2.19 uV, or about 7 dBu.

Ns is a measure of how much greater the actual set noise is relative to thermal noise (Nt). The above values are those that the FCC assumed to be typical of TV receivers in the late 1950's.

Snr is the desired signal-to-noise ratio. The FCC chose to use a 30 dB ratio, which corresponds closely to a TASO Grade 3 or "passable", which is described as: "The picture is of acceptable quality: Interference is not objectionable." That, of course, was the judgement of non-technical observers in a study completed over 40 years ago.

Kd is the "dipole factor", the conversion factor between field strength (measured in terms of volts per meter) and volts across the output terminals of the antenna.

G is the assumed gain of a typical receiving antenna. The FCC assumptions (6 dB at VHF and 13 dB at UHF) imply fairly elaborate antenna designs.

L is the assumed transmission line loss.

ΔT is the time-variability factor. Grade B and Grade A contour signal strength specifications are based on a 90% time-availability factor.

ΔL is the location-variability factor. The Grade B signal strength values are based on a 50% requirement.

The corresponding development of required signal strength for Grade A (70% of the locations, as opposed to 50% for Grade B) results in values of 54, 64, and 74 dBu for Channels 2-6, Channels 7-13 and UHF, respectively. There is, however, the interesting footnote that an additional 14 dB of signal strength is required to overcome urban noise at low-VHF (Channels 2-6) and 7 dB at high-VHF (Channels 7-13). Therefore, the final signal strength requirement for non-rural reception (that is, the Grade A contour) was adjusted upward to the final values of 68 dBu for Channels 2-6 and 71 dBu for Channels 7-13. It is likely that actual urban noise levels have increased significantly since the FCC's analysis was completed, along with a somewhat comparable reduction in internal set noise. In particular, man-made noise levels may have increased at UHF frequencies (Channel 14-69) because of the onslaught of digital electronic equipment (e.g., personal computers) in the typical household.

The lack of adequate signal strength (within the Grade B contour, as predicted in accordance with Section 73.684 of the FCC Rules), will be found to be the causative factor of poor reception in only a minority of the cases. Other factors, such as multi-path reception ("ghosts"), urban noise (as contrasted with thermal and receiver noise), and interference (including that from other television stations) will found to be the dominant reasons for unacceptable picture quality. Therefore, the FCC should focus on techniques by which picture quality can be quantitatively determined, rather than on the difficult (and relatively meaningless) signal strength measurement task.

Quality of service acceptable to viewers may have changed

The majority of American households no longer rely on over-the-air reception of television. Cable TV and Satellite-to-Home services have replaced the home antenna almost completely. The resulting high quality of received picture has probably changed viewer's perception of picture acceptability during the forty-two years that have passed since viewer acceptance tests were conducted by the Television Allocations Study Organization (TASO). (About half of the observations were of monochrome pictures!) The FCC's channel allotment planning factors were based on a 30 dB signal to noise and interference ratio, which corresponds closely to TASO Grade 3: "Passable - The Picture is of acceptable quality. Interference is not objectionable".

It is suggested that the modern median viewer would consider a TASO Grade 2 picture ("The picture is of high quality providing enjoyable viewing. Interference is perceptible") to be the minimum acceptable quality. TASO Grade 2 corresponds to a signal to noise and interference ratio of approximately 36 dB. However, the noise performance of television receivers has improved significantly as compared with the noisy vacuum tube technology on which the Grade B standard is based. Roughly stated, improvements in receiver noise factors (on the order of 6 dB) and this suggestion that today's viewers expect less snow on their pictures, just about cancel. Thus, were it not for man-made ("Urban") noise, the Grade B signal strength values would still be pertinent.

"Required Reading" regarding the effects of surface clutter upon radiowave propagation

SHVIA specifies that " the Commission shall rely on the Individual Location Longley-Rice model set forth by the Federal Communications Commission in CS Docket No. 98-201, and ensure that such model takes into account terrain, *building structures, and other land cover variations*." The effects of buildings and vegetation ("surface clutter") upon the propagation of radiowaves has been the subject of numerous studies and technical papers. In my opinion, there are at least two such reports that should be studied before a serious discussion of this subject can be undertaken. The first such work, historically, is Howard T. Head's 1960 study[1] the influence of trees on UHF television signals. Later (in 1978) Anita G. Longley[2], co-author of the Longley-Rice model, published a comprehensive review of earlier work on radio propagation in urban areas. Neither of these highly original works, however important they may be to the discussion at hand, is readily available. Therefore, they have been scanned using an optical character reader and are attached hereto as Attachment 1 and Attachment 2, respectively.

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[1] Head, H. T. (1960), "The Influence of Trees on Television Field Strengths at Ultra-High Frequencies" Engineering Report A. D. Ring and Assoc, Consulting Engineers, Washington, DC. (A version of this work was later published in the June, 1960 issue of "Proceedings of the IRE")

[2] Longley, Anita G. (1978), "Radio Propagation in Urban Areas", OT Report 78-144, United States Department of Commerce, Office of Telecommunications

Head's analysis of the influence of trees on UHF TV signals

Howard T. Head's 1960 paper discussed UHF Television signal strength data, collected in and near bands of trees in the vicinity of Salisbury, Maryland. He found that there is a very rapid decrease of signal strength upon entry to a band of trees from the unobstructed side and that attenuation asymptotically approaches a more-or-less constant value of about 30 dBin the subject case. Upon leaving the band of trees, on the shadowed side, the signal recovers slowly, in a manner very similar to diffraction over a knife-edge.

The Longley "Urban Factor" modification to the Longley-Rice Model

Along with her excellent overview of the work of others, Longley developed an "Urban Factor" correction to the basic Longley-Rice mode (See "Radio Propagation in Urban Areas, Section 3.2 A Computer Prediction Model."). Longley's urban factor, UF, increases smoothly with increasing frequency, and decreases with increasing distance from the transmitter. With frequency (f) in MHz and distance (d) in km this relationship was expressed quantitatively as

$$UF = 16.5 + 15 \text{ Log}(f/100) - 0.12d \text{ dB}$$

The Longley Urban Factor and how it was developed.

In her discussion of existent radio propagation models, Longley introduced the Okumura model as follows:

> "Extensive studies of land-mobile radio services in Japan have been reported by Okumura et al. (1968), and by Kinase (1969). Measurements at 200, 453, 922, 1310, 1430, and 1920 MHz, were made in the heart of Tokyo and its environs. Okumura et al. show the effects of "environmental clutter" in urban, suburban, and open areas for various frequencies, antenna heights, distances, and terrain types. They define an open area as clear for 300 to 400 m from the receiving antenna, a suburban area includes villages with scattered trees, and an urban area is a built-up city crowded with large buildings, two-story houses, and tall trees. (Until recently, the maximum building height in Japan has been 31 m.) Measured values of field strength in urban areas, over smooth terrain, are plotted versus path length for each frequency at several transmitting antenna heights with a 3 m receiving antenna. From these measurements they derived a set of curves of median attenuation relative to free space as a function of frequency for various distances in an urban area over practically smooth terrain. For a frequency range of 100 to 1000 MHz, the attenuation is 6 to 10 dB less in suburban areas, while in open areas it is 23 to 29 dB less than in an urban area. They note that the variability of the signal increases with frequency, and that there is less loss on radial than on cross streets."

With respect to the development of the proposed "urban factor", Longley stated:

> "Because these prediction curves[3] have been widely accepted, and are interrelated as shown, we compared values of attenuation relative to free space calculated for non-urban areas using the modified Longley-Rice computer model, with those read from Okumura's curves, Figure 1, for an urban area. For both models we assumed rather smooth terrain with effective antenna heights of 200 m and 3

[3] i.e., Okumura

m. Values were obtained for frequencies from 100 to 3000 MHz, and for distances up to 100 km. As expected, the Okumura urban curves show greater attenuation. The differences between the two models may be considered as representing the additional power loss in an urban area, and referred to as an "urban factor". The values listed in Table 2 show this factor for each frequency and distance."

Table 2 is reproduced, below:

Urban Factor: A(Okumura)-A(Longley-Rice) dB
Frequency

d km	100	150	200	300	500	1000	2000	3000 MHz
10	16.2	17.4	20.6	22.9	26.6			
20	13.4	15.9	18.2	20.6	24.1	29.4	36.3	
30	11.5	14.3	16.4	19.1	22.7	27.4	34.0	38.3
40	10.9	13.4	15.3	17.9	21.5	26.0	31.9	35.7
50	10.0	12.8	14.8	17.5	20.7	25.3	30.7	34.2
60	9.3	12.1	13.5	16.4	19.4	24.0	29.1	32.2
70	8.6	11.2	12.8	15.3	18.2	22.5	26.2	28.8
80	8.0	10.6	12.0	14.2	16.4	20.0	22.7	24.3
90	7.3	9.4	10.7	12.0	13.8	16.9	18.5	19.4
100	6.5	7.7	8.3	10.0	11.2	13.5	14.1	15.2

$h_1 = 200$ m, $h_2 = 3$ m

In substance, Longley conformed the predictions of the Longley-Rice model to the graphical results of Okumura's superb analysis of a massive collection of field strength measurement data. In so doing, she introduced ad hoc "corrections" to the basic Longley-Rice model.

As an example of these (unintentional) "correction factors", let us consider the Longley-Rice treatment of reflections off the surface of the earth. The model assumes that there is a spectral reflection point on a plane that is defined by a least-squares fit to the height of the terrain along the propagation path at hand. No attempt is made to determine whether such a reflection could exist, even though the details of the terrain profile are available. In the case of a typical urban location, with the transmitting antenna much higher than the receive antenna, the hypothetical reflection point would be located near the receiver, in an area quite probably immersed in more urban clutter. The propagation path from reflection point to receiver is almost certainly entirely within the clutter (with the accompanying signal attenuation), whereas the direct transmitter-to-receiver path might well be totally unobstructed. The result, then, that there is often no significant plane-earth reflection to be considered, even though the Longley-Rice assumes otherwise. Thus, Longley's "Urban Factor" involves more than just a quantification of the signal strength loss due to urbanization.

The above discussion is not intended as a criticism of the outstanding professional work of Longley and Rice and their co-workers. It is, however, important to recognize that while the Longley Urban Factor ("the LUF") is an important step toward improving our ability to accurately predict the behavior of radiowaves in a realistic environment, improvements to that formulation will undoubtedly be possible as more data becomes available.

Regarding Section III-B Improvements in the Model

At NPRM ¶10, the FCC suggests a reorganization of the Land Use-Land-Cover (LULC) categories in a way specifically relevant to radio propagation. After regrouping, only 10 of the original 37 categories remain.

I endorse the proposed simplification of LULC categories. However, I suggest that consideration be given the heights that are typical of each classification and whether the cover is vegetation, buildings or a flat surface (e.g., water), as summarized below:

FIPS LUC	FCC LUC	FIPS Landuse Description	Class	1000 MHz Loss_dB	Height Meters
00		Not Available	flat	0.0	0.0
11	7	Residential	urban	29.5	24.4
12	9	Commercial/Services	urban	29.5	15.0
13	9	Industrial	urban	29.5	15.0
14	1	Transportation	urban	29.5	15.0
15	9	Industrial/Commercial	urban	29.5	15.0
16	8	Mixed Urban	urban	29.5	15.0
17	8	Other Build-up Land	urban	29.5	15.0
21	2	Cropland/Pasture	veget	15.7	1.2
22	2	Orchard/Vineyard	veget	29.5	5.0
23	2	Feed Lot	flat	15.7	0.0
24	2	Other Agricultural	veget	15.7	1.2
31	3	Herbaceous Range	veget	15.7	1.2
32	3	Shrub/Brush Range	veget	15.7	1.2
33	3	Mixed Range	veget	15.7	1.2
41	5	Deciduous Forest	veget	29.5	24.4
42	5	Evergreen Forest	veget	29.5	24.4
43	5	Mixed Forest	veget	29.5	24.4
51	4	Stream/Canal	flat	0.0	0.0
52	5	Lake	flat	0.0	0.0
53	4	Reservoir	flat	0.0	0.0
54	4	Bay/Estuary	flat	0.0	0.0
61	5	Forested Wetland	veget	29.5	24.4
62	6	Nonforested Wetland	flat	15.7	1.2
71	1	Dry Salt Flat	flat	0.0	0.0
72	1	Beach	flat	0.0	0.0
73	1	Sandy Area Not Beach	flat	0.0	0.0
74	1	Bare Rock	flat	0.0	0.0
75	1	Strip Mine/Quarry	veget	29.5	24.4
76	1	Transitional	veget	29.5	24.4
77	1	Mixed Barren Land	flat	0.0	0.0
81	1	Shrub/Brush Tundra	flat	0.0	0.0
82	1	Herbaceous Tundra	flat	0.0	0.0
83	1	Bare Ground Tundra	flat	0.0	0.0
84	1	Wet Tundra	flat	0.0	0.0
85	1	Mixed Tundra	flat	0.0	0.0
91	10	Perennial Snowfields	flat	0.0	0.0
92	10	Glaciers	flat	0.0	0.0

Where:

FIPS LUC is the Federal Information Processing Standards code number for the land-use classification at hand.

FCC LUC is the corresponding classification, proposed by the FCC in the instant proceeding.

1000 MHz Loss is the estimated excess path loss ("clutter loss") for a "penetration angle" of 0.5 degrees. The penetration angle is defined as the downward vertical angle between the tangent to the radio horizon (including clutter height) and the receiving antenna, as viewed from the transmitter center of radiation. For negative values of penetration angle (i.e., the receiving antenna has clear line-of-sight to the source), clutter loss becomes zero.

The clutter height for residential land-use assumes that there are shade trees near the houses. No consideration was made of the height of cows in the feedlot category. It should be noted that a "flat" land-use would be capable of supporting a spectral reflection, whereas vegetation-covered or urban areas would be expected to cause diffuse reflections, if any.

The height of the "clutter" becomes important when it is recognized that excess path loss is a function of the distance traveled through the clutter. Unfortunately, the heights of objects within a given land-use classification vary widely from place to place, and the above-suggested heights are just that. It is expected that high quality worldwide terrain height and land cover data will become available as a result of NASA's Shuttle Radar Topography Mission, launched in February 2000.

Suggested penetration parameters are as follows:

Penetration Factors

Deg.	Flat	Veget.	Urban
0.0	1.225	1.250	1.260
0.5	1.000	1.000	1.000
1.0	0.622	0.812	0.856
1.5	0.335	0.699	0.737
2.0	0.000	0.624	0.657
2.5	0.000	0.560	0.594
3.0	0.000	0.505	0.538
3.5	0.000	0.450	0.482
4.0	0.000	0.403	0.434
4.5	0.000	0.358	0.390
5.0	0.000	0.313	0.355
5.5	0.000	0.273	0.315
6.0	0.000	0.235	0.279
6.5	0.000	0.194	0.247
7.0	0.000	0.160	0.215
7.5	0.000	0.126	0.102
8.0	0.000	0.092	0.102

Note that the penetration loss factors, above, show a significant decrease as a function of increasing angle, as was also observed by workers cited by Longley (1978), Figures 2 and 3).

Longley also noted that the excess path loss due to clutter has a strong frequency dependence and suggested a value of (16.5 + 15 Log(f/100)) dB (along with a small distance-dependent factor), where f is the frequency in megahertz . My independent analysis of large collections of mobile field strength measurement data, gathered in a variety of physical environments and at frequencies ranging from 35 to 880 MHz, has resulted in a frequency factor of 15.5 dB. Because frequency bands presently in use extend to approximately 2,000 MHz, I chose to use 1000 MHz as the scaling factor, for which case the suggested clutter loss is adjusted by 15.5 Log(f/1000) dB. (If the calculated loss is less than zero, it is set to zero.)

The close agreement between Longley's clutter-loss frequency factor and my own independently developed value is, to say the least, striking. A close reading of Longley (1978) will reveal that other workers have observed similar frequency factors (e.g., Kinase (1969)). Kinase's graphical depiction of median value of clutter effect as a function of frequency (See Longley (1978) Figure 3) strongly suggests that the frequency slope is itself a function of frequency. The slopes of Kinase's frequency factors (which are themselves functions of the percentage of area occupied by clutter) are steeper in the frequency range 400-1000 MHz than either the Longley or Biby factors and they appear to asymptotically approach a lesser value, dependent on clutter density, at lower frequencies.

Longley based her suggested frequency factor on a comparison of the predictions of the Longley-Rice model with the graphs prepared by Okumura. Okumura's work involved measurements at six frequencies (200, 453, 922, 1310, 1430, and 1920 MHz), of which only three are with the 100-1000 MHz frequency band of interest in Longley (1978). It would seem logical, therefore, that Longley's frequency factor was based on no more than three points (200, 453, and 922 MHz).

Similarly, the data on which my (15.5 dB) factor was based was heavily weighted toward the 880 MHz region (Cellular Mobile Radiotelephone signaling frequencies), 88-108 MHz (FM Broadcast), and 35-40 MHz (Public Safety Land Mobile frequencies). It is suggested that perhaps Kinase (1969) is closer to the truth of the matter than either Longley or myself.

It is likely that Longley's suggested "urban factor" and my own approach lead to similar results and that the real case is more complex than either approach recognizes. In order to expedite the matter (and in recognition of that fact that the data presently available is simply not sufficient to allow a definitive solution), I urge that Longley's urban factor ("LUF") be used with the following adjustment to the basic Longley-Rice prediction, based on the ILLR Clutter Category at the receive point:

ILLR Category Number	ILLR Category Description	Adjustment
1	Open Land	0.5*LUF
2	Agricultural	0.5*LUF
3	Rangeland	0.5*LUF
4	Water	0
5	Forest Land	LUF
6	Wetland	0
7	Residential	LUF
8	Mixed Ubran/Buildings	LUF
9	Commercial Industrial	LUF
10	Snow and Ice	0

A Fortran 90 computer program that generates Longley urban factor (LUF) attenuation values, based on Longley's Table 2A, is attached as Appendix C – Subroutine Longley Clutter.

Discussion of the Rubinstein Clutter Loss Values

At NPRM ¶11, the FCC proposes to adopt clutter loss values based on the results published in a recent engineering journal by Thomas N. Rubinstein[4]. The Commission states: "…the available data for assigning values to these parameters is limited, and we believe it is reasonable to assign values only in situations for which measurement data have been analyzed and published, or for which we have some confidence in deriving such values…" and then immediately proceeds to extrapolate the Rubinstein data outside the frequency range explored in the subject study. That is simply not good engineering practice.

The Commission goes on to state: "Since the Rubinstein values of clutter loss are derived exclusively from measurements made at receiver sites with Fresnel clearance, the values should apply only to matching situations. For other situations, the clutter loss will have to remain equal to the default value of zero dB, the value it effectively has in the current ILLR model where LULC data is not used."

There is no evidence known to me that would suggest that clutter losses disappear when the path begins to become less than perfectly clear. Therefore, I urge that the model use the Longley Urban Factor, adjusted for land-use classification as suggested above, for all paths. As is discussed elsewhere in these comments, the Commission should require that sufficient data be collected so as to provide a firm basis for improvements in the model.

The Man-Made Noise Factor in Television Reception

The definitive source on the subject of radio noise is "Man-Made Radio Noise", by Edward N. Skomal (Van Nostrand Reinhold, New York). Mr. Skomal provides graphical representations of the measured noise across the radio frequency spectrum in business, residential and rural areas. (He defines residential areas as those locations of single- or multiple-family dwellings with densities of two families or more per acre, while rural areas are those having a dwelling density of one or fewer per 5 acres with an associated land use that is dominantly agricultural.) According to Skomal, typical median man-made noise levels are:

Channel	Rural	Residential	Business
2	20 dB	25 dB	30 dB
13	3 dB	8 dB	13 dB

Rubinstein (1998), in addition to providing data regarding observed clutter attenuation factors as a function of land-use classification, reported the results of extensive ambient noise measurements. Noise data were gathered at a frequency of 162 MHz in Southern California (SCA), Northwest Washington State (NWW) and in the Atlanta, Georgia metro area (ATL). Rubinstein's noise data have been categorized as being in Rural, Residential, or Business (and other urbanized) areas and average values determined for each case, as follows:

[4] Thomas N. Rubinstein, "Clutter Losses and Environmental Noise Characteristics Associated with Various LULC Categories," *IEEE Transactions on Broadcasting*, Vol. 44, No. 3, September 1998.

Area	Rural	Residential	Business
SCA	15.8	15.6	16.0
NWW	11.9	12.1	13.3
ATL	12.3	12.6	13.5
Skomal	8.0	13.0	18.0

The data for Northwestern Washington and Atlanta are in close agreement, while the Southern California noise levels are about 3 dB higher. This does not necessarily mean that Southern California is actually noisier than the other two areas; it may be that typical clutter attenuation values in California are less (due to the relatively sparse vegetation in the San Diego and Los Angeles areas where the data was collected). Noise propagates just like any other form of electromagnetic energy, so the California samples might reflect larger noise source areas than is the case for the other two.

It is also interesting that the Rubinstein data shows very little difference among rural, residential and business areas. In fact, Skomal's residential noise estimate appears to be a reasonably good general representation for all three categories, at least for the population of points and the one frequency used in Rubinstein's study.

A Fortran 90 program that calculates the Skomal noise estimate, based on land-use classification and population density, is attached as Appendix A, Subroutine Get_noise

FCC Predictive Model Should Consider Urban Noise

Man-made noise should be included in the Commissions predictive model. I suggest that Skomal's values be used because they are based on the most extensive study of the subject known to me.

Multipath Considerations

Multipath reception – "ghosting" – is possibly an even more prevalent cause of unsatisfactory television reception than is man-made noise. Ghosting, in which one or more secondary images are seen, generally displaced to the right of the main picture, is due to the difference in path length between the direct path and signals being reflected off objects not on the direct path. (Objects along the direct path cause a shadow effect, that is, a decrease in signal strength, but no ghost.)

American analog (NTSC) pictures standards result in a left-to-right edge scanning time of about 54 μsec. Since radiowaves travel at a speed of 300 meters/second (about 984 feet), an object with a path length 4050 meters (about 2.5 miles) longer than the direct path would cause a "ghost" image displaced one-forth of a picture width to the right of the main signal.

Captions with character sizes on the order of fifty or more to a picture width are fairly common in modern-day television, or about 1.0 μsec per character. In that case, a ghost having a time delay of less than 0.25 μsec (a total of about 246 feet) would seriously impair the readability of the message. In other words, signals bouncing off the house across the street can make that fine print on the TV ads illegible!

Ghosts are more visible than random noise ("snow") because the ghost image is present, in the same place, all the time. Random noise is likely to cause any given spot on the image to be lighter during one scan and darker the next, so that the human perceptual process tends to average things out. In contrast, the perception of the ghost image is reinforced frame after frame after frame.

How the Model can be extended to detect multipath "ghosts"

In order for a multipath signal to be visible, two things are necessary: 1) there must be a time-delay relative to the main signal; and 2) it must have sufficient strength to be discernable. Unfortunately, no studies known to be have been made regarding viewer tolerance of either of these parameters.

A likely candidate for causing ghosting is an object, any object, tall enough to reach above the local clutter so as to have a direct line-of-sight path to the source. The signal along the above-the-clutter portion that will be much stronger than the signal at a nearby household immersed in the clutter. Also, such objects (e.g., buildings, hills or mountains, transmission towers, etc.) are typically large; the total amount of signal energy available for them to scatter can be very much greater than the energy intercepted by the (much smaller) TV receiving antenna.

The reflector-to-house path is at least partially through the local urban/vegetation clutter, and so the reflection suffers attenuation on that part of its travel. Based on the slant-range attenuation characteristics of the local clutter, it is possible to estimate the area , more or less centered on the receive location, within which tall objects would be likely to cause problems. Thus, another reason for the attractiveness of the concept of the penetration angles through the clutter, as was introduced in the earlier discussion of the Longley Urban Factor.

Transmission towers, be they for radio/TV broadcast, Cellular telephone systems, or power lines, are a prime cause of ghosting. Clearly, mountainous terrain and tall buildings are others. Fortunately, both the FAA and the FCC maintain databases of towers, and the FAA database even includes unusually tall buildings.

An approach to predicting the potential for multipath reception at a given household proceeds as follows:

1) Based on the terrain around the house and the characteristics of the local clutter, estimate the area within which ghost generation is likely to be a problem.
2) Examine that area for possible troublesome objects, using the available tower, terrain and land-use databases. For example, business/commercial land-use typically includes structures that are tall enough to cause ghosts at nearby households

The Model should consider interference from other TV stations

Desired/undesired ratios of -3 dB, +28 dB, and -13 dB for lower adjacent, co- and upper-adjacent channel interference, respectively, are specified in FCC OET Bulletin No. 69, "Longley-Rice Methodology for Evaluating TV Coverage and Interference", July 1997. (These ratios are intended for channel allotment purposes, and do not represent a standard of picture acceptability.)

Suggested measurement methodology: noise and co-channel interference

The key to my suggested measurement methodology is the ability to capture digitized picture frames from the TV signal. Several companies, including Hauppauge Computer Works, Inc., offer very sophisticated circuit boards that are essentially complete TV receivers. Because they are designed to work in conjunction with computers, at least some of these boards have the ability to capture TV signals in digital format. (Details regarding Hauppauge's WinTV boards can be found at www.hauppauge.com.)

Signal-to-Noise ratios are determined by performing a Fast Fourier Transform (FFT) on a "quiet line", that is, a horizontal scan line with no picture modulation and comparing those data with blanking level or peak-of-sync. Because the original viewer preference tests ("the TASO tests") were based on carrier-to-noise ratios, it would be necessary to determine the S/N ratio acceptable to viewers, based on this proposed measurement methodology.

Desired/Undesired Co-channel signal strength ratios can also be gleaned from the FFT. The FCC's TV channel allotment system ensured (in general) that neighboring assignments on the same channel are required to operate with a 10 kHz carrier frequency separation, so as to minimize the visibility of the interfering signal. Thus, the interfering carrier will usually be found at +/-10 KHz (and possibly at +/- 20 KHz) in the demodulated TV baseband signal spectrum.

An alternative method of determing carrier signal strengths and their ratios is based on the use on the Winradio PC-based communications receivers. (Details regarding the WinRadio receiver boards can be found at www.winradio.com.) These devices cover the frequency range from 150 KHz to 1.5 GHz and are of instrumentation quality. They provide a signal measurement capability that is accurate enough for SHVIA Grade B signal-strength purposes. If necessary, a reference generator can be used to create a more precise calibration of the unit's digital signal strength indication. Clearly, this approach provides a direct measurement of desired and undesired adjacent channel signal strengths.

Desired/Undesired Co-channel signal strength ratios are easily measured, using the Winradio Digital Suite, an optional software package that includes a spectrum analyzer with a typical 80 dB dynamic range and the ability to resolve signals separated by just a few Hertz.

Suggested measurement methodology: multipath "ghosting"

It is my understanding that most television stations in the United States transmit a "ghost-cancellation" signal during the vertical retrace interval. The only problem is that, until recently, no chips were available for incorporation into TV receivers to take advantage of the ghost-canceling system. To my knowledge, the only manufacturer presently supplying such chips is Oren Semiconductor, Inc. (Santa Clara, CA www.oren.com). Oren offers the following

> "Background on the Video Ghost Problem
> NTSC and PAL are the most common legacy video standards used in terrestrial analog television broadcast. With these standards, video is transmitted as a RF carrier modulated by the video baseband signal. Noise or distortion in the signal at the receiver will directly affect the video display. One of the most difficult distortions to avoid in terrestrial broadcast is signal multi-path, which causes video "ghosts" in the display. Signal multi-path is the reception of a transmitted signal via multiple propagation paths, received at slightly different times. This is common problem in urban or mountainous regions where strong signal reflections occur.
> Ghost cancellation can be performed at the receiver by removing unwanted multi-path signals in the baseband video, prior to decoding. To assist in the ghost cancellation process, a Ghost Canceller Reference (GCR) signal is inserted, just prior to transmission, during the vertical-blanking interval. The receiver compares the received GCR against an internally stored GCR and adjusts a large equalization filter until the two are nearly identical. There are various GCR signal broadcast standards that have been adopted internationally. Device programs are available for the OR43200 that cover all GCR standards and all versions of NTSC and PAL. Currently, Oren Semiconductor is the only supplier

of ghost cancellation devices compatible with the GCR standards used outside Japan."

The signals that are used to adjust the equalization filter in the ghost-cancellation chip provide a means of quantifying the extent of the ghosting present.

Comments Regarding Specific Paragraphs in NPRM

At NPRM ¶11, the Commission invites comment on its proposal to use clutter loss values for low band channels that are derived by applying frequency trend data (as found by Okumura) to the Rubinstein clutter loss values for high band VHF. Unfortunately, to do so requires that the Rubinstein data be extrapolated outside its frequency range. It is never good engineering practice to extrapolate data outside the range of experience. I urge that the Commission adopt the Longley Urban Factor, adjusted for land-use classification, as discussed above.

At NPRM ¶13, the Commission seeks comment on its proposal to use a formal rule making process to make changes in the future in the ILLR model adopted in this proceeding. Even though it is cumbersome and time-consuming, I believe that the rule making process is the appropriate administrative mechanism to this end.

Data now being collected by NASA's Shuttle Radar Topography Mission (SRTM) is expected to result in worldwide availability of 30-meter grid terrain and land-use data within no more than two years. Clearly, that represents an enormous improvement over presently available 3-arc second terrain and (twenty or so year old) 200-meter grid cell land-use data. Availability of the SRTM terrain and land-use data would, for example, be a good reason to re-examine the model.

I urge that the Commission adopt the estimates of the effects of clutter as developed in Longley (1978). The Commission should also require that signal measurement data be collected in a tightly specified manner at large numbers of representative locations, so as to provide a basis for further improvements in the model.

At NPRM ¶15, the Commission addresses the question of how to identify entities qualified to conduct signal tests if the satellite carrier and the network station are not able to agree on the eligibility of a given household for imported network service.

Herein lies an opportunity for the FCC acquire data on which to base further improvements in its' predictive model. With the "loser pays" rule now firmly in place, it would appear to be in everyone's best interests to improve the predictive model, if possible, to such an extent that the number of contested cases is minimized.

Unfortunately, there is simply no known body of measurement data, taken in typical home receiving environments, on which to base a statement of acceptance criteria and performance standards. I am confident that, if appropriate (reliable) data were to be collected, the predictive model can be modified to reach the level of "presumptive correctness."

Therefore, I suggest that the FCC require signal strength and quality measurements be performed at some percentage of those households that qualify for service on the basis of the proposed improvement of the ILLR model. There is, within the context of pertinent court decisions, the Satellite Home Viewer Improvement Act of 1999, and FCC regulations, no particular reason to focus on those households that are served/unserved on the basis of the existent ILLR model.

The widest applicability of the predictive model will be in those markets where the satellite providers do not expect to be able to provide local-into-local service in the near future. According to available sources, it is expected that only the top twenty to thirty markets are to be offered local-into-local within the next few years, which leaves a population of about forty million

(40,000,000) households that are candidates for satellite service. Also, there are a many people who expressed a desire for service but were denied or who once received service but were terminated because of court order(s). Finally, it has been stated that there are about three million (3,000,000) households presently receiving network service imported from out-of-market via satellite. Clearly, there is a large body of potential test locations.

<u>What percentage of these household locations should be tested?</u>

There should be enough data collected to provide a basis for improvement of the model, but there is no sense in collecting excessive amounts of data that cannot be utilized. Something on the order of one household location in one thousand to one in one hundred would be about right, in addition to the contested cases.

<u>What data should be collected?</u>

As has been discussed, signal strength, signal-to-noise, signal-to-co-and adjacent-channel interference, and ghosting cancellation data should be collected. Certain details regarding methodology are discussed with respect to specific portions of NRPM, below.

<u>What types of qualifications should person taking measurements possess?</u>

I urge that the Commission expand its definition of testing procedure to include measurements of noise, ghosting and other-station interference and that there be some specification of the training that persons performing the tests must have. There are companies that specialize in training people to perform task such as these. Those firms are also prepared to test the skills of their trainees and certify their competence.

<u>What characteristics will demonstrate the independence and neutrality contemplated by the statute?</u>

In addition to proper training, as discussed above, the measurement process should be so automated as to leave little possibility for error or misrepresentation. For example, the location of the test can be determined by means of a Global Positioning Satellite receiver and recorded automatically by the computer-controlled test set. There can be a requirement that a digital camera be used to show the environment in the direction of the TV station(s). The orientation of the test receiving antenna can be determined electronically and recorded by the computer without operator intervention. The list of potential local network serving stations (and possible interfering stations) can be built into the computer test-management program. The tests themselves (noise, station interference, ghosting, and signal strength) can be highly automated (and monitored) to such an extent as to virtually guarantee valid testing.

As a further guarantee, there could be spot-checking of sample test location by FCC Engineering personnel.

<u>Should there be multiple designating entities across the country or one central clearinghouse?</u>

There is no obvious reason why there should not be multiple designated entites.

<u>Comments regarding Appendix A,Technical Data, Prediction of Field Strength</u>

I urge that the Commission reconsider step 3) of this procedure, which eliminates from further consideration those paths lacking 0.6 first Fresnel clearance. As is so eloquently developed in Head (1960), vegetation (and by extension, urban) clutter is virtually opaque to (UHF) radio waves for all except for very thin screens of clutter. (I state on my own knowledge that this statement is also true at VHF) As was also shown by Head, the most common mode of propagation in cluttered environments is <u>over</u> the clutter, with the final portion of the path being either by scatter off the surface of the clutter (and thence downward through the clutter) or essentially a knife-edge diffraction mechanism over the clutter. The receiving antenna in a typical cluttered environment is, in effect, underground in "clutter-earth". In truth, locations that would fully meet the proposed 0.6 Fresnel zone clearance are rare in cluttered environments.

Further, while it is true that the magnitude of clutter loss may be somewhat less for obstructed paths than for line-of-sight paths, the clutter loss does not disappear. Until more data is available on this subject, I urge that the FCC allow consideration of paths that do not have full terrain clearance.

<u>Comments regarding the test receiving antenna</u>

The FCC Rules require that the test antenna be elevated to 30 ft. (9 meters) above ground for a two (or more) story house, or 20 ft. (6 meters) in the case of a one-story house. This require-ment troubles me from a personnel safety perspective. I am aware of no substantive data that shows a generally acceptable height-gain function in cluttered environments for such a small increase in height. However, it is true that there are many fewer high-voltage wires at 20 ft. than there are at 30 ft. above ground. The Commission should re-consider this antenna height requirement in order to avoid possible needles tragedies.

SHIVA specifies that, in the event that if reception of more than one local network station is to be tested, a stationary antenna should be used. The commission should provide guidance on how the stationary antenna is to be oriented.

<u>Regarding terrain data point spacing</u>

A note in NPRM Appendix A states:

> "Terrain elevation data at uniformly spaced points the between transmitter and receiver must be provided. The ILLR computer program must be linked to a terrain elevation database with values every 3 arc-seconds of latitude and longitude or closer. The program should retrieve elevations from this database at regular intervals with a spacing increment of 0.1 kilometer (parameter XI in Table 1). The elevation of a point of interest is determined by linear interpolation of the values retrieved for the corners of the coordinate rectangle in which the point of interest lies."

I caution the FCC against trying to discern that which is not there. We have no knowledge of what the terrain elevation is between the database points and we should not try to divine those intermediate elevations. I urge that the requirement that the elevation of a point be determined by linear interpolation of the corner values be dropped. It is sufficient to simply take the database elevation value in which the point at hand is located.

The 0.1 kilometer requirement is fine, but needs some clarification. For example, a rigid application of the 0.1 km requirement will (generally) result in the final point in the terrain data profile not being coincident with the location of the subject household. I suggest that this requirement be changed to read somewhat as follows:

> "The program should retrieve elevations from this database at N+1 regularly spaced intervals, where N = 10.0 times the path length is in kilometers from source to subject household."

Respectfully Submitted

. February 20, 2000

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```
! Subroutine Get_Noise
! Purpose: When called with latitude/longitude, frequency (MHz) and a "density class" based on land-use code at
! receive point,  this routine returns the man-made noise level as calculated according to "Man-Made Noise" by
! E.N. Skomal.  It fetches a one-bit flag from a housing density database to determine whether location meets
! Skomal's definition of residential/rural.

subroutine get_noise(house_lat,house_lon,freq_mhz,density_class,noise_db)
implicit none
save
real, parameter slope=-27.7
integer, parameter completed=0,rural=1,residential=2,business=3,one=1
real  house_lat,house_lon,freq_mhz,noise_db,us_sw_lat,us_sw_lon
integer density_map(175500),density_class,pop_bits,map_lat_index,&
        map_lon_index,map_index,now_density,density_unit,density_stat
logical been_here=.false.

if(been_here)goto 1
! Read the housing density bit map.
call get_lun(density_unit)
open(density_unit,file='c:/data/census/house_density.dat',form='binary',&
        iostat=density_stat)
if(density_stat <> completed)then
        write(6,100)'house_density.dat',density_stat
100 format('could not open ]',a,'[  Status: ',i5)
        stop 'fatal error'
end if
read(density_unit,iostat=density_stat)density_map
if(density_stat.ne.completed)then
        write(6,101)density_stat
101     format(' Error on read of house_density file. Status: ',i5)
        stop
end if
close(density_unit)
been_here=.true.

1 us_sw_lat=24.0000
us_sw_lon=-126.0000
if(density_class == 0)then
        map_lon_index=anint((house_lon-us_sw_lon)*60.)
        map_lat_index=anint((house_lat-us_sw_lat)*60.)
        map_index=(3600*map_lat_index)+map_lon_index
        now_density=pop_bits(map_index,one,density_map)
        density_class=rural
        if(now_density .ne. 0)density_class=residential
end if
! Residential and business class noise levels are 5.0 and 10.0 dB greater than rural class, respectively, so first
! calculate the rural case.
noise_db=40.0+(slope*alog10(freq_mhz/10.0))
if(density_class .eq. residential)noise_db=noise_db+5.
if(density_class .eq. business)noise_db=noise_db+10.
if(noise_db .lt. 0.0)noise_db=0.0
return
end
```

```
subroutine longley_clutter(luc,freq_mhz,dx_km,clutter_db)
!  Purpose:    Returns an estimate of excess path loss due to land-use and  clutter, based on Anita G. Longley's paper
! "Radio Propagation in  Urban Areas", April, 1978.
! Programmer:  Richard L. Biby, P.E.
! Written for the PC environment, January, 1999.

implicit none
save

real        freq_mhz,dx_km,clutter_db,db_1000_mhz(10),slope(10),db_adjust(0:99),&
            decades,db_ref,per_unit_dx,delta_slope,slope_at_dx,db_lower,db_upper,&
            delta_db,ref_db
integer     luc,class,ix_dx

data slope / 15.7,15.7,15.7,15.7,15.7,14.9,14.0,11.7,9.6,7.2/
data db_1000_mhz/31.3,29.0,27.3,26.3,25.6,24.0,22.5,20.0,17.1,13.5/
data db_adjust/ 21*1.0,0.5,1.0,11*0.5,17*1.0,4*0.0,7*1.0,0.5,8*1.0,4*0.0,2*1.0,23*0.0/

decades=alog10(freq_mhz/1000.)
if(dx_km .le. 10.)then
            clutter_db=db_adjust(luc)*(db_1000_mhz(1)+decades*slope(1))
            return
else if(dx_km .ge. 100.)then
            db_ref=db_1000_mhz(10)
            clutter_db=db_adjust(luc)*(db_1000_mhz(10)+decades*slope(10))
            return
end if

ix_dx=dx_km/10.
per_unit_dx=(dx_km-10*ix_dx)/10.

! Attenuation vs. frequency slope depends only on distance.
delta_slope=slope(ix_dx)-slope(ix_dx+1)
slope_at_dx=slope(ix_dx)-per_unit_dx*delta_slope
db_lower=db_1000_mhz(ix_dx)
db_upper=db_1000_mhz(ix_dx+1)
delta_db=db_upper-db_lower
ref_db=db_lower+(per_unit_dx*delta_db)
clutter_db=db_adjust(luc)*(ref_db+decades*slope_at_dx)
return
end
```

```
! Function tv_freq
! function to convert from integer TV channel number to visual carrier
! frequency (mHz)
real function tv_freq(n_chan)
implicit none
save

if(n_chan .le. 4)then
        tv_freq=6*(n_chan-2)+55.25
        return
end if

if(n_chan .le. 6)then
        tv_freq=6*(n_chan-5)+77.25
        return
end if

if(n_chan .le. 13)then
        tv_freq=6*(n_chan-7)+175.25
        return
end if

 tv_freq=6*(n_chan-14)+471.25
 return
end
```

APPENDIX A

THE INFLUENCE OF TREES ON TELEVISION FIELD STRENGTHS AT ULTRA-HIGH FREQUENCIES

By
Howard T. Head

THE INFLUENCE OF TREES ON[5] TELEVISION FIELD STRENGTHS AT ULTRA-HIGH FREQUENCIES

By Howard T. Head, Partner, A. D. Ring & Associates
Consulting Radio Engineers, Washington, D.C.

Introduction

One of the more serious aspects of the problem of providing television service at the ultra-high frequencies has been the failure in many instances to obtain r.f. field strengths within the service areas as high as predicted by classical propagation theory. It has been generally appreciated that rough terrain and heavy vegetation have depressing effects on the received signal. The recognition of the effects, however, has been mainly qualitative, with no clear understanding of the absolute or relative magnitudes of the respective losses.

Recent work by LaGrone[6] at the University of Texas and others has provided a reasonable quantitative assessment of the influence of rough terrain on the received signal[7]. However, even after due allowance has been made for the reduction of signal caused by rough terrain, the observed median field strength is often still substantially below that predicted by classical theory. LaGrone, in his report to the Television Allocations Study Organization, recommends that smooth-earth predictions at the ultra-high frequencies (470 mc to 890 mc for television service) be reduced by 22 decibels to provide basic curves from which further departures due to terrain irregularities are predicted.

Experimental Program

To determine how much UHF signal reduction might be ascribed to the effects of trees, a program of field strength measurements was undertaken in the vicinity of Salisbury, Maryland, during December 1958 and January 1959. This area was selected (see Figure 1) because the terrain is very flat, because new topographic maps showing woodland cover were available, and because a television transmitting station (WBOC-TV) was in operation with a transmitting antenna height (620 feet above terrain) reasonably characteristic of stations in regular operation. The transmitter operates on television channel 16, which occupies the frequency band from 482 mc to 488 mc. The visual and aural-carrier frequencies are 483.26 mc and 487.76 mc, respectively. The radiated power is approximately 20 kW essentially omnidirectional in the horizontal plane.

Field strength measurements on the WBOC-TV signal were made at locations selected to provide transmission under varying conditions over, through and around woods. At each location selected for measurement, the field strengths were measured using a short mobile run in accordance with the measuring technique specified by Panel 4 (Propagation Data) of the Television Allocations Study Organization. In a few instances where the mobile run was impractical, a "cluster" of spot measurements was substituted. The use of the mobile run or "cluster" technique introduces an averaging process which tends to smooth out small-area variations caused by standing wave patterns or other local influences.

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[5] This work was sponsored by the Association of Maximum Service Telecasters, Inc.

[6] A.H. LaGrone, “Forecasting Television Service Fields” Final Report TASO/UT Contract, December 31, 1958

[7] Other references dealing with terrain losses are listed in the bibliography.

All of the measurements were made with a receiving antenna height of 30 feet above ground. The details of the equipment and technique utilized in making these measurements have been described in a previous article.[8]

Measurements were made over transmission paths which fall into three general categories:

(a) Unobstructed ray paths between transmitting and receiving antennas;

(b) Ray paths obstructed by groups of trees sufficiently small that the signal would be propagated principally through, rather than around, the trees (these are referred to as "thin screens" of trees); and

(c) Ray paths obstructed by groups of trees sufficiently large that the signal would be propagated principally around, rather than through, the trees (these are referred to as "thick screens" of trees).

Measuring locations in this last category were chosen so that the obstructing mass of trees occurred at varying distances from the receiving antenna in the direction of the transmitting antenna. The distance from the receiving antenna to the woods is referred to as the clearing depth" (see Figure 3).

Discussion of Results

A survey of the literature reveals only scant references to the effect of trees and foliage on the received signal at the ultra-high frequencies. Trevor[9] in the United States and Saxton and Lane[10] in Great Britain have published results showing the attenuation of the signal when the transmission path is entirely through vegetation. Some classified NDRC reports from World War II include similar data. The available data are reasonably consistent and show relatively severe attenuation of signals at these frequencies when the transmission path lies entirely through trees and underbrush. The conclusions, as summarized by Saxton and Lane, are shown in Figure 2.

Measurements were made at 13 locations in the Salisbury area of the attenuation of the signal in passing through thin screens of trees ranging in thickness from 8 meters to 480 meters. The results of these measurements are in reasonably good agreement with the conclusions of Saxton and Lane, but the rate of attenuation shows a decreasing trend with increasing woods thickness. This variation is probably due principally to the fact that the typical television transmission path is basically different from that for the condition where both the transmitting and receiving antennas are surrounded by trees.

In the latter situation, the entire ray path must pass through the obstructing vegetation. For typical television transmission, however, only a small part of the transmission path may pass through trees and underbrush. The transmitting antenna is usually several hundred feet high, and only within a few miles of the receiving antenna is the signal obliged to cope with trees and underbrush near the ground. This is illustrated in Figure 3, which shows a typical ray path for transmission between television transmitting and receiving antennas. For a path such as shown, substantial amounts of the signal may be diffracted over and around the trees. The presence of the diffracted signal is most noticeable when the vegetation is so dense as to reduce the signal transmitted through the trees to a very low value.

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[8] H. T. Head, "Measurement of Television Field Strength", Electrical Engineering, Vol. 77, No. 4, pp. 298-302, April 1958

[9] B. Trevor, "Ultra-High Frequency Propagation Through Woods and Underbrush", RCA Review, pp. 90-92, July 1940

[10] J.A. Saxton and J.A. Lane, "VHF and UHF Reception Effects of Trees and Other Obstacles", Wireless World, Vol. 61, No. 5, pp. 229-232, May 1955

The first measurements made in the Salisbury area were intended to permit a determination of the signal arriving at the receiving antenna in terms of the attenuation in passing through various thicknesses of woods. Examination of the first results, however, showed little correlation with woods thickness and a comparison with the Saxton and Lane curve (Figure 2) revealed that the thicknesses being employed were so great that the signal arriving through the woods should be well below the noise level of the measuring equipment; nevertheless, measurable signals were being received. A further study of the measurements showed that the relative signal levels were lowest when the receiving antenna was closest to the edge of the woods between the transmitting and receiving antennas, increasing as the clearing depth (see Figure 3) increased.

A preliminary analysis showed the signal to increase approximately in proportion to the logarithm of the clearing depth for clearing depths greater than approximately 0.01 mile, but at very close distances to the woods the signal level appeared to be more or less unrelated to the clearing depth. This is illustrated by Figure 4, which shows the difference between the smooth earth predictions and the actual observations plotted versus the logarithm of the clearing depth. The straight line is a least-squares fit to the data points beyond 0.01 mile. The standard deviation from the line is 4.1 decibels.

Comparison with Diffraction Theory

The basic theory of the diffraction of electromagnetic energy around the edge of a partially or completely opaque object is well established. Particular solutions, however, have been obtained only for a number of special cases, and the typical practical problem may bear little resemblance to the idealized situations for which theoretical solutions have been derived. Also, it is often difficult to foretell from the geometry of the practical case which of the particular theoretical solutions represents the model most closely resembling actual transmission conditions.

The Salisbury data were separated into two groups. In the first group were the thin screen measurements, in which it appeared that the received signals represented so complex a combination of transmitted and diffracted signals that they would have little value in a diffraction analysis. The remaining measurements, consisting of the thick screen measurements and unobstructed ray path measurements, were grouped together and tabulated. For each observation, there was determined the depression of the measured field below the smooth-earth value (ΔSE), the depression of the field below the free-space value (ΔFS), and the ratio of the obstruction of the trees in the first Fresnel zone to the radius of the zone at the point of maximum obstruction (H/Ho). Graphs of these values were plotted and compared with attenuation curves representing various modes of diffraction[11 12].

A plot of ΔSE versus H/Ho does not exhibit particularly good correlation with the theoretical diffraction curves. However, a plot of ΔFS versus H/Ho shows that for Fresnel zone clearances greater than about -1.0 the points tend to fall in the general region of the theoretical curves for diffraction around a smooth sphere. Figure 5 is a plot of this relationship showing a comparison with theoretical diffraction around a smooth spherical obstacle for a reflection coefficient R = -1 and a value of Bullington's parameter M of M = 300.

The parameter M is a function of transmitting and receiving antenna heights, frequency and radius of the spherical obstacle. For the heights and frequency at Salisbury, a value of M = 300

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[11] K. Bullington, "Radio Propagation Fundamentals", Bell System Technical Journal, Vol. 36, *No. 3,* P'P* 593-626, May 1957

[12] A. I. Kalinin, "Approximate Methods of Computing the Field Strength of Ultra Short Waves with Consideration of Terrain Relief", RADIOTEKIINIKA, Vol. 12, No. 4 *pp. 13-26,* 1957

corresponds to a smooth sphere having a radius of 24 miles. The standard deviation of the observed values from the theoretical curve is 3.4 dB for Fresnel zone clearances in excess of -1.0.

The observed data were next compared with diffraction theory making the assumption that the trees exhibit some sort of "edge effect", due to the thinness of the upper branches, the small diameter of the top of the trunks, or other causes. Most of the tree heights for the transmission paths at Salisbury had been determined by actual measurements with a Matthews Teleheight, and the average tree heights were approximately 55 feet. The actual tops of the trees were thus some 25 feet above the receiving antenna height of 30 feet above ground.

The values of H/Ho were redetermined assuming the existence of an "edge effect" of 10 feet; this would result in an apparent average height of the trees of 45 feet above ground, or 15 feet above the receiving antenna. The redetermined values of H/Ho were then plotted against ΔFS and the plot compared with the theoretical diffraction curves.

Figure 6 shows a comparison of the observed values for the redetermined values of H/Ho with the theoretical smooth-sphere diffraction prediction for M = 50. This value of M corresponds to diffraction around a sphere having a radius equal to 4/3 of the earth's radius, the value customarily assumed in classical theory for propagation through a standard atmosphere. The standard deviation of the observed values from the theoretical curve is 2.9 dB for Fresnel zone clearances greater than -0.6.

It will be noted from Figure 6 that the attenuation is substantially less than predicted on the basis of smooth-sphere diffraction for Fresnel zone clearance less than approximately -0.6. These values of Fresnel zone clearance represent locations where the receiving antenna was very close to the obstructing mass of trees, generally within 100 feet or less. In several instances, the receiving antenna was within 10 feet of the nearest edge of the woods.

In this region, the attenuation exhibits little correlation with any of the parameters influencing the other fields. It appears likely that the field received near the edge of the woods arrives at the receiving antenna principally through the tops of the woods and over a number of irregular paths. In making this portion of the measurements, it was frequently observed that the receiving antenna did not exhibit any clear maximum and minimum as the antenna was rotated; in many instances it was not possible to identify the direction toward the transmitter from the orientation of the receiving antenna. The signal arriving under these conditions has been referred to as the "leakage field" (Fl) because it appears to leak through the tops of the trees, often in a rather erratic fashion.

The measurements which were considered to represent principally leakage field were analyzed for any evident trends. An examination of eight observations of leakage field at distances ranging from 12.0 miles to 22.5 miles from the transmitter indicated the average signal level below the calculated smooth-earth field to be more or less independent of distance. For these eight points, the average depression of the field below the smooth-earth field was approximately 30 dB, with a standard deviation of 3.3 dB.

Extension of Theory

These observations and conclusions provide a basis for predicting loss of UHF signal strength where the loss is due primarily to the effects of trees. Consider a transmission path such as shown in Figure 7a. Between the transmitting antenna and the first woods at the distance D1 there is no obstruction, and the received fields in this region are those predicted by smooth-earth theory. Beyond Dl, in the woods**,** the received signals are primarily those arriving through the woods, and the attenuation increases rapidly with woods thickness until the leakage field level is reached (D2). The attenuation cannot exceed that corresponding to the leakage level and thus any additional woods thickness does not result in further depression of the signal.

Beyond the distance D3, where the far edge of the woods is reached, the received signals recover with distance in an approximately logarithmic fashion until the clearing depth is sufficient that the smooth-earth values are once again approached. This logarithmic recovery, which is noted in Figure 4, can be shown to follow as a consequence of diffraction; the relationship is determined by the geometry associated with the distance between transmitter and receiver.

This model of the behavior of the field permits drawing some interesting conclusions. First, in an area completely covered with trees or essentially so, the received signal would be largely governed by the leakage level. This level is probably a function of frequency and also of the type of vegetation. If this latter is the case, as seems likely, the leakage fields would be expected to be lower in the spring and summer than in the fall and winter. It seems probable that the relationship of the leakage field to the frequency would be similar to that for attenuation in passing through thin screens of trees as shown in Figure 2.

If the forest cover is less than 100%, some receiving locations will be closely surrounded by trees and others partly in the clear. Theoretical models of the type shown in Figure 7b were set up, and the effects of various sequences of woods and clearing were determined on the basis of the processes suggested. These studies showed that the average attenuation in an area with Pf per cent forest cover, in which the leakage field is denoted by Fl, cannot be less than PfFl/100 for any sequences of woods and clearing reasonably to be expected. For unfavorable sequences, the attenuation maybe higher than this value, but an upper limit of attenuation is set by the relationship between the decay and recovery characteristics shown in Figure 7b. The average attenuation as a function of per cent forest cover based on this model of the behavior of the field is shown in Figure 8. The straight line corresponds to the least attenuation of the signal for the most favorable sequence of woods and clearing, and the dashed line the highest attenuation to be expected for the most unfavorable sequence for a given percentage of forest cover. The dotted line shown in Figure 8 is an average attenuation curve falling between the two limits.

Conclusions

Using Figure 8, an estimate can be made of the average attenuation of the UHF signal due to the effect of trees, provided that an estimate of the percentage of forest cover can be made. Although some modifications will probably be required for other frequencies and for vegetation under other conditions, it can be seen that the average attenuation due to the trees is on the order of the 22 decibels below smooth-earth values employed by LaGrone. It appears likely, based on these findings and the model of attenuation derived from them, that forest attenuation may be one of the most significant factors responsible for the average loss in signal at the higher frequencies.

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/4 H. T. Head, "Measurement of Television Field Strength", Electrical Engineering, Vol. 17, No. 4, pp. 298-302, April 1958

/5 B. Trevor, "Ultra-High Frequency Propagation Through Woods and Underbrush", RCA Review, pp. 90-92, July 1940

/6 J. A. Saxton and J. A. Lane, "VHF and UHF Reception Effects of Trees and Other Obstacles', Wireless World, Vol. 61, No. 5, pp. 229-232, May 1955

/7 K. Bullington, "Radio Propagation Fundamentals”, Bell System Technical Journal, Vol. 36, No. 3, pp. 593-626, May 1957

/8 A. I. Kalinin, "Approximate Methods of Computing the Field Strength of Ultra Short Waves with Consideration of Terrain Relief", Radiotekhnika, Vol. 12, No. 4 pp. 13-26, 1957

(The numbers refer to the numbered footnotes in the article)

TABLE I

Observed Attenuation of Signal
Through Thin Screens of Trees

(1)	(2)	(3)	(4)	(5)	(6)	(7) .
1	15.5	1	8	13	50%Pine – Measurement made at 10’	Cluster
2	14.,2	6	10	.60	50% Pine	Cluster
3	15.5	4.5	20	.225	50% Pine	Cluster
5	14.2	17	90	.19	65% Hardwood	Mobile
6	15.5	15.5	130	.12	70% Pine, Dense- Measurement Made at 10’	Mobile
7	14.2	6	150	0.025	Hardwood	Mobile
8	25.5	18.5	150	.12	Pine	Mobile
9	12.5	23.5	183	.13	Dense Pine, Needles antenna height	Mobile
10	16.5	17	210	.08	Dense Hardwood	Mobile
11	27.5	30	300	.10	Hardwood	Mobile
12	12.0	24.5	310	.072	Dense Pine	Mobile
13	14.5	20	480	.04	50% Hardwood	Mobile

(1) Observation Number
(2) Distance from Transmitter - Miles
(3) Total Screen Attenuation - dB
(4) Thinness of Woods Cover - Meters
(5) Rate of Attenuation - dB/Meter
(6) Character of Woods
(7) Type of Measurement
Receiving antenna height is 30 feet above ground unless otherwise noted.

Measurements made in December 1958 – January 1959
Salisbury, Maryland – 482 –486 mc.

TABLE II
OBSERVED ATTENUATION OF SIGNAL
THROUGH THICK SCREENS OF TREES

(1) .	(2) mi.	(3) dBu	(4) dBu	(5) dBu	(6) dBu	(7) dB	(8) . mi	(9)	(10) .
1	12.0	50	83	81	33	31	Neg.	-3.0	-6.0
2	12.0	80	83	81	3	1	1.7	+.59	+.48
3	12.5	52	83	81	21	29	0.11	- .46	- .87
4	12.5	76	83	81	7	5	0.7	+.20	+.034
5	14.2	67	81	80	14	13	0.6	+.055	-.13
6	14.4	47	81	80	34	33	Neg.	-3.0	-6.0
7	14.5	47	81	80	34	33	Neg.	-3.0	-6.0
8	14.5	75	81	80	6	5	0.8	+.19	+.032
9	14.9	72	80	79	8	7	0.8	+.16	0
10	15.0	55	80	79	25	24	Neg.	-2.1	-4.0
11	15.7	52	80	79	28	27	Neg.	-3.0	-6.0
12	15.7	76	80	79	4	3	1.9	+.47	+.37
13	16.7	47	78	78	31	31	Neg.	-2.1	-4.0
14	16.7	64	78	78	14	18	1.2	+.19	+.065
15	18.6	67	76	77	9	10	2.45	+.38	+.25
16	19.8	62	75	77	13	15	2.0	+.23	+.13
17	20.05	42	75	77	33	35	0.05	-1.08	-1.84
18	20.15	49	75	77	26	28	.15	-.44	-.82
19	20.2	54	75	77	21	23	.225	-.32	-.62
20	20.2	52	75	77	23	25	.25	-.31	-.58
21.	20.3	51	75	77	24	26	.28	-.26	-.53
22	20.3	51	75	77	24	26	.32	-.22	-.46
23	20.35	51	75	77	24	26	.35	- .21	-.44
24	20.45.	56	74	77	18	21	.45	-.15	-.36
25	20.55	56	74	76	18	20	.55	-.115	-.31
26	20.65	53	74	76	21	23	.65	-.088	-.26
27	20.75	54	74	76	20	22	.75	-.049	-.21
28	22.25	48	72	76	24	28	.25	-.31	-.58
29	22.3	63	72	76	9	13	.8	-.079	-.24
30	22.3	54	72	76	18	22	.3	-.275	-.525
31	22.35	53	72	76	19	23	.35	-.23	-.465
32	22.45	53	72	76	19	23	.45	-.19	-.40
33	22.5	45	72	76	27	31	.023	-1.3	-2.3
34	22.55	57	72	76	15	19	.55	-.13	-.33
35	22.65	54	72	76	18	22	.65	-.088	-.26
36	22.75	57	71	76	14	19	.75	-.065	-.23
37	22.85	57	71	76	14	19	.85	-.046	-.20
38	22.95	60	71	76	11	16	3.6	+.27	+.195
39	23.0	64	71	76	7	12	3.6	+.27	+.195

TABLE II
OBSERVED ATTENUATION OF SIGNAL
THROUGH THICK SCREENS OF TREES

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8) .	(9)	(10)
.	mi.	dBu	dBu	dBu	dBu	dB	mi		.
40	23.1	60	71	76	11	16	1.1	-.027	-.16
41	23.25	61	71	76	10	15	1.25	0	-.13
42	23.35	60	71	76	11	16	1.35	+.012	-.11
43	23.45	60	71	76	11	16	1.45	+.036	-.083
44	23.55	59	70	75	11	17	1.55	+.057	-.057
45	23.65	60	70	75	10	16	1.65	+.067	-.057
46	25.4	58	68	75	10	17	1.0	-.071	-.21
47	29.85	37	63	74	30	37	.13	-.54	-.92
48	29.9	52	63	74	11	22	1.2	-.13	-.26
49	31.3	49	62	73	13	24	2.05	-.089	-.19
50.	31.3	40	62	73	22	33	.15	-.53	-.89
51	31.65	40	61	73	21	33	.15	-.53	-.89
52	31.75	44	61	73	17	29	.25	-.42	-.69
53	31.85	47	63.	73	14	26	.35	-.35	-.58
54	31.95	47	61	73	14	26	.45	-.32	-.53
55	32.05	46	61	73	15	27	.55	-.29	-.48
56	32.25	48	61	73	13	25	.75	-.23	-.39
57	32.35	50	61	73	11	23	.85	-.215	-.37
58	32.45	50	60	73	10	24	.95	-.19	-.34
59	32.55	49	60	73	11	24	1.05	-.18	-.32
60	32.65	48	60	73	12	25	1.15	-.17	-.305
61	35.4	49	57	72	8	23	2.4	-.175	-.27
62	35.6	46	57	72	11	26	.55	-.31	-.50
63	35.7	49	57	72	8	23	2.6	-.17	-.255
64	36.2	56	56	72	3	19	3.2	-.17	-.25
65	36.3	18	56	72	48	54	Neg.	-3.0	-6.0

/1 Reduced to 1 kW radiated
(1) Observation Number
(2) Distance from Transmitter
(3) Measured Field strength
(4) Calculated Field Strength - Smooth Earth
(5) Calculated Field Strength - Free Space
(6) $-\Delta SE$
(7) $-\Delta FS$
(8) Depth of Clearing
(9) Fresnel zone Clearance - assumed 45-foot trees
(10) Fresnel zone Clearance - 55-foot trees

Measurements made in December 1958 - January 1959,
Salisbury, Maryland, 482 – 486 mc

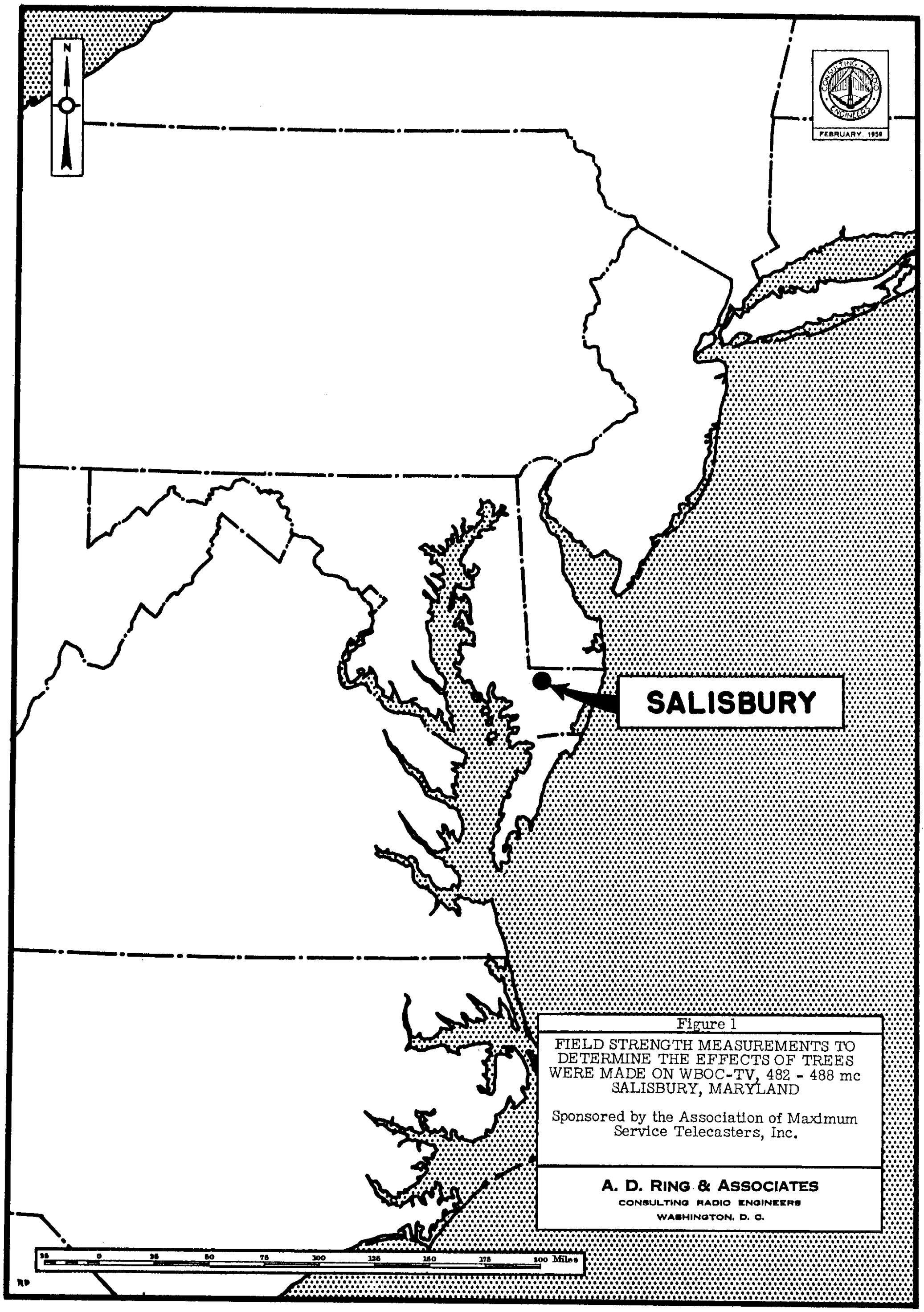

Figure 1

FIELD STRENGTH MEASUREMENTS TO DETERMINE THE EFFECTS OF TREES WERE MADE ON WBOC-TV, 482 - 488 mc SALISBURY, MARYLAND

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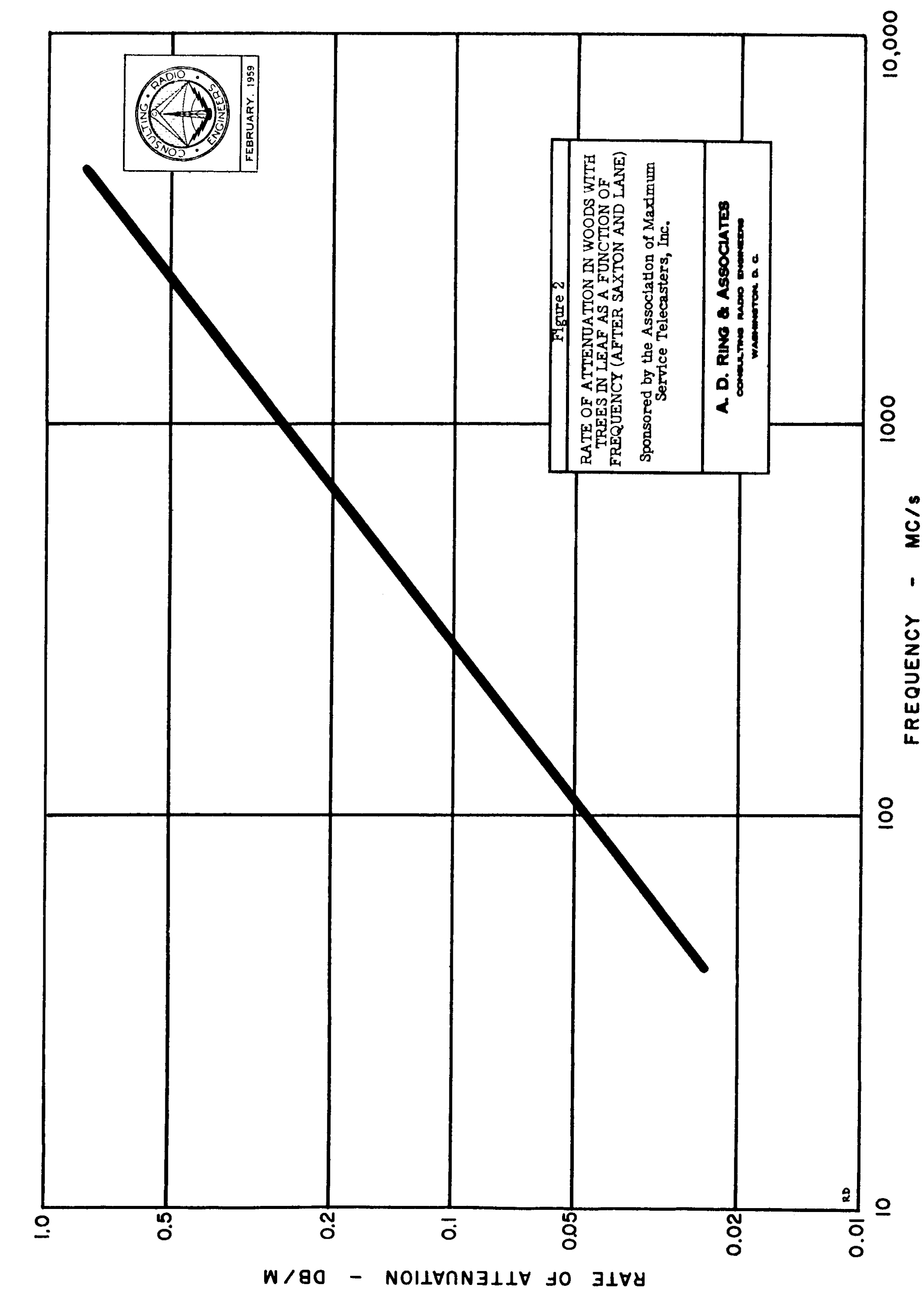
Figure 2
RATE OF ATTENUATION IN WOODS WITH TREES IN LEAF AS A FUNCTION OF FREQUENCY (AFTER SAXTON AND LANE)
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FEBRUARY, 1959
1.0
0.5
0.2
0.1
0.05
0.02
0.01
RATE OF ATTENUATION - DB/M
10
100
1000
10,000
FREQUENCY - MC/s

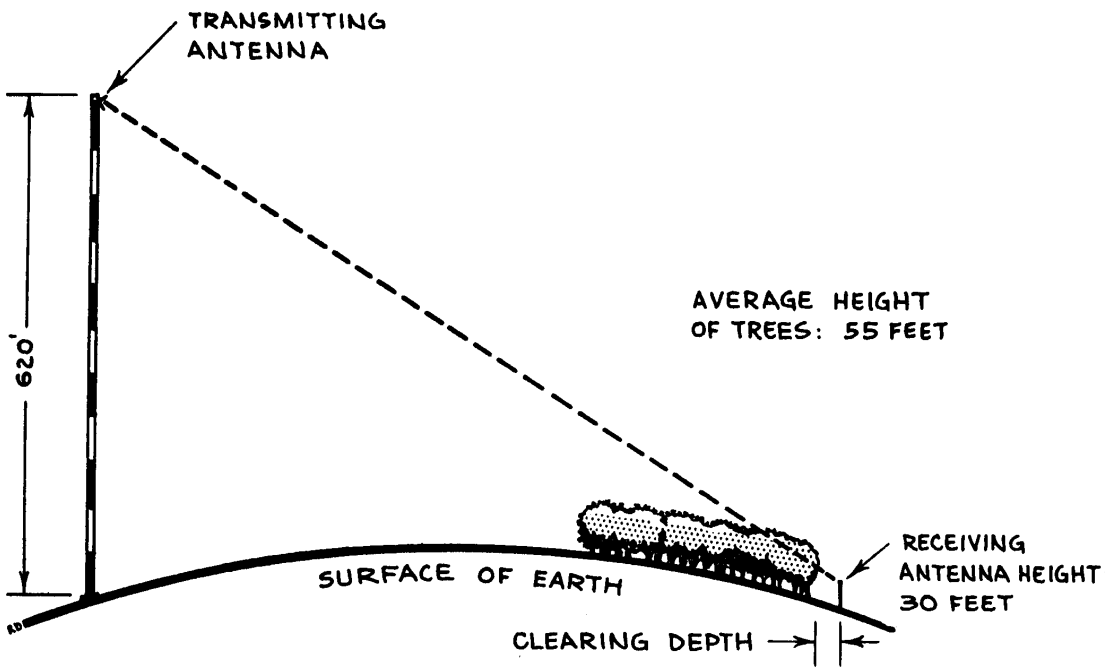

Figure 3

THE TYPICAL TELEVISION TRANSMISSION PATH IS BASICALLY DIFFERENT FROM THAT WHERE BOTH TRANSMITTING AND RECEIVING ANTENNAS ARE SURROUNDED BY TREES

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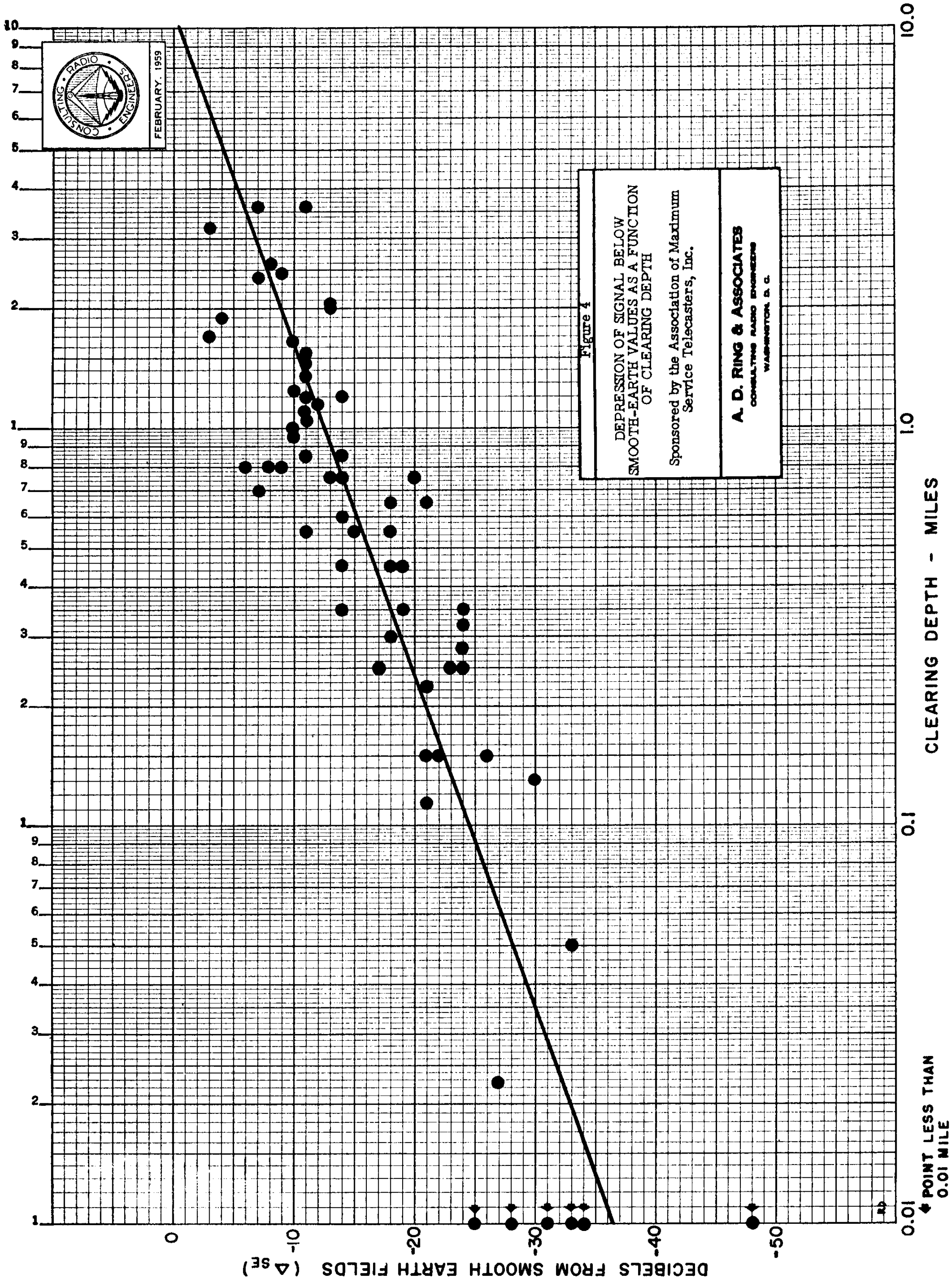
Figure 4
DEPRESSION OF SIGNAL BELOW SMOOTH-EARTH VALUES AS A FUNCTION OF CLEARING DEPTH
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FEBRUARY, 1959
CLEARING DEPTH - MILES
0.01
0.1
1.0
10.0
DECIBELS FROM SMOOTH EARTH FIELDS (Δ SE)
0
-10
-20
-30
-40
-50
POINT LESS THAN 0.01 MILE

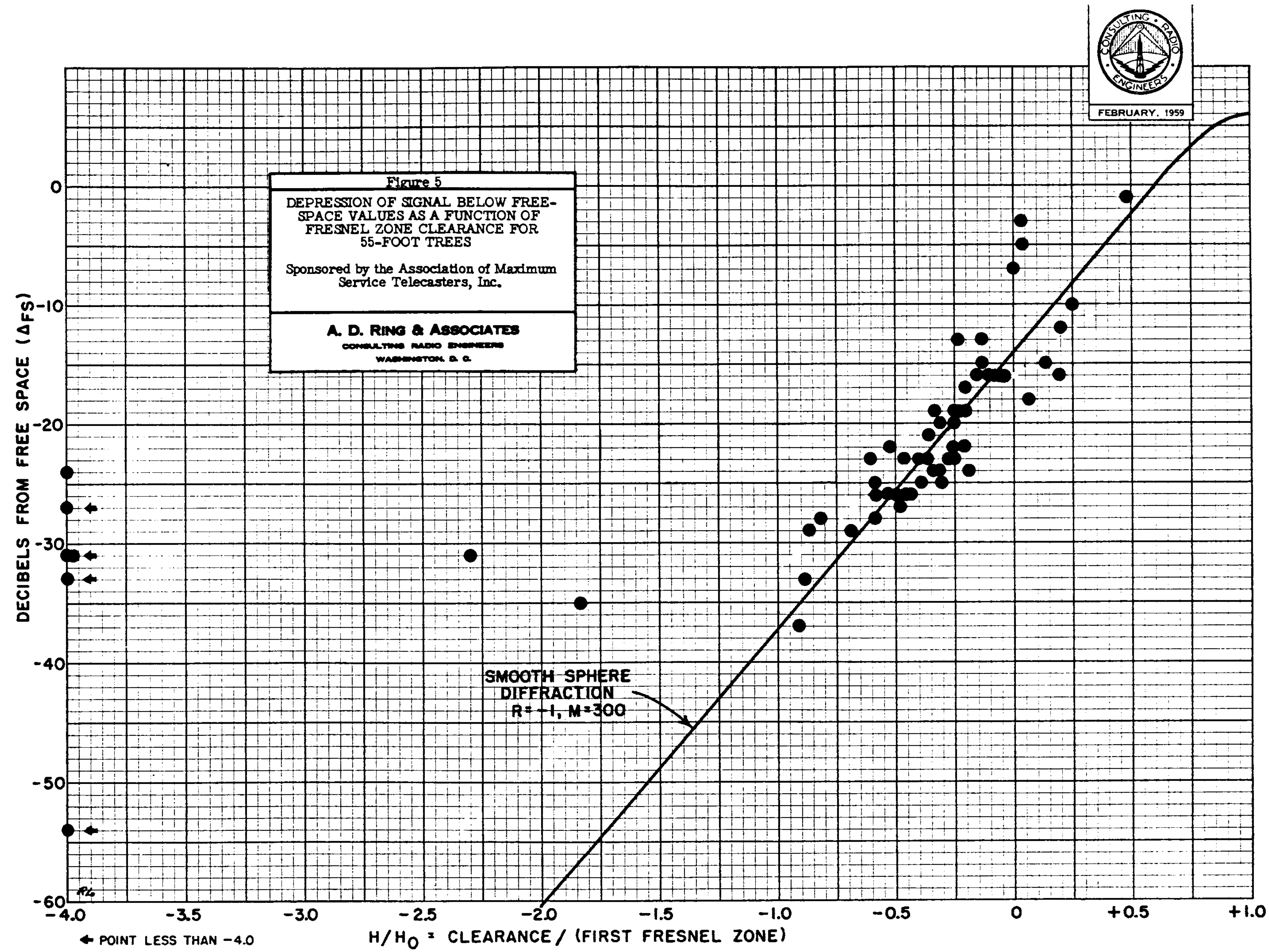

Figure 5
DEPRESSION OF SIGNAL BELOW FREE-SPACE VALUES AS A FUNCTION OF FRESNEL ZONE CLEARANCE FOR 55-FOOT TREES
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FEBRUARY, 1959
SMOOTH SPHERE DIFFRACTION R=-1, M=300
DECIBELS FROM FREE SPACE (Δ_{FS})
0
-10
-20
-30
-40
-50
-60
-4.0
-3.5
-3.0
-2.5
-2.0
-1.5
-1.0
-0.5
0
+0.5
+1.0
H/H$_0$ = CLEARANCE / (FIRST FRESNEL ZONE)
← POINT LESS THAN -4.0

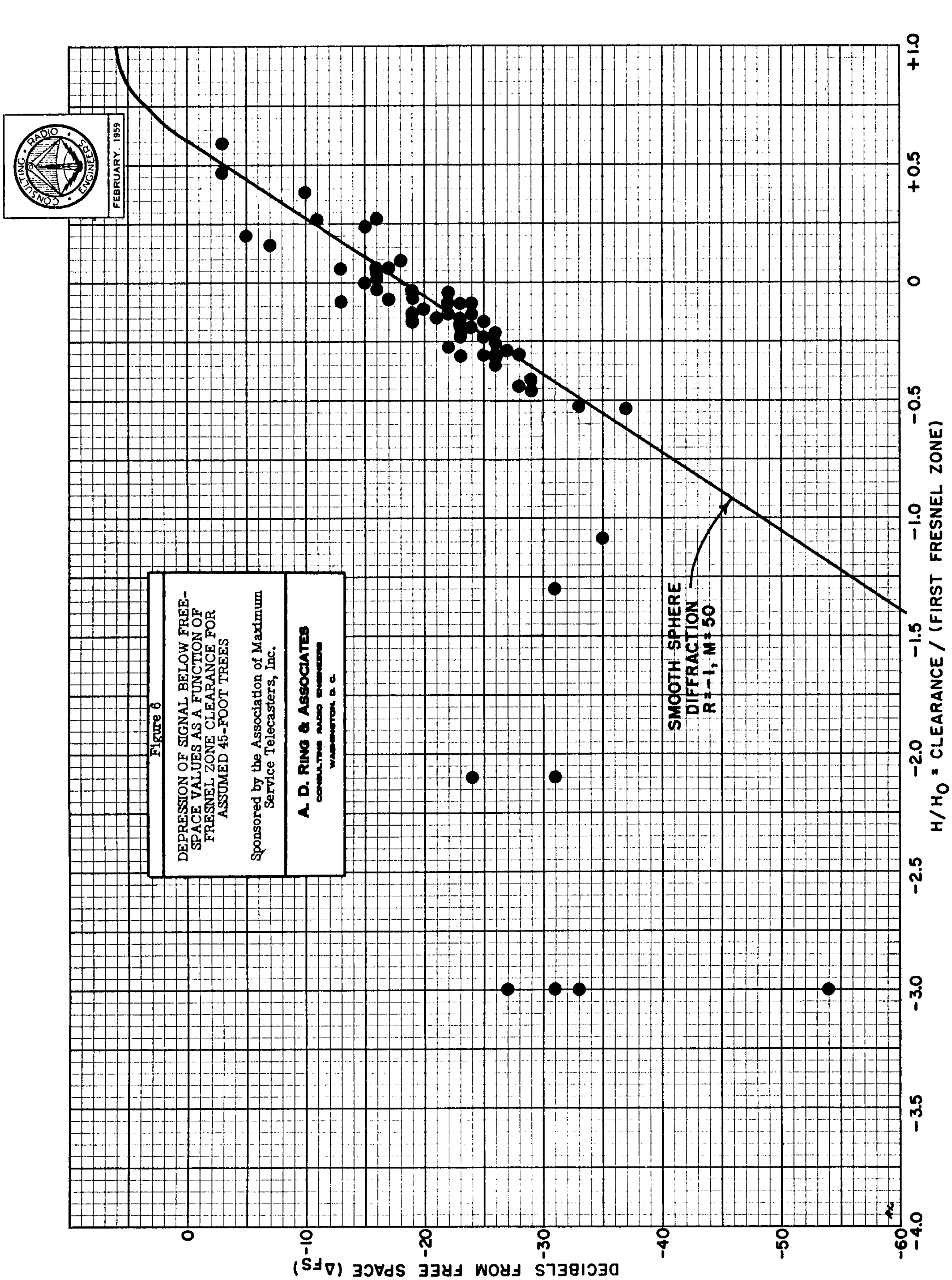

Figure 6
DEPRESSION OF SIGNAL BELOW FREE-SPACE VALUES AS A FUNCTION OF FRESNEL ZONE CLEARANCE FOR ASSUMED 45-FOOT TREES
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FEBRUARY, 1959
SMOOTH SPHERE DIFFRACTION R = -1, M = 50
DECIBELS FROM FREE SPACE (A_{FS})
0
-10
-20
-30
-40
-50
-60
H/H_O = CLEARANCE / (FIRST FRESNEL ZONE)
-4.0
-3.5
-3.0
-2.5
-2.0
-1.5
-1.0
-0.5
0
+0.5
+1.0

FEBRUARY, 1959

FIG. 7(a)

FIG. 7(b)

Figure 7

(a) MODEL OF WOODS-AND-CLEARING FOR ESTIMATING AVERAGE WOODS ATTENUATION

(b) DEPRESSION OF SIGNAL BELOW SMOOTH-EARTH VALUES VERSUS DISTANCE FOR THE MODEL OF FIGURE 7(a)

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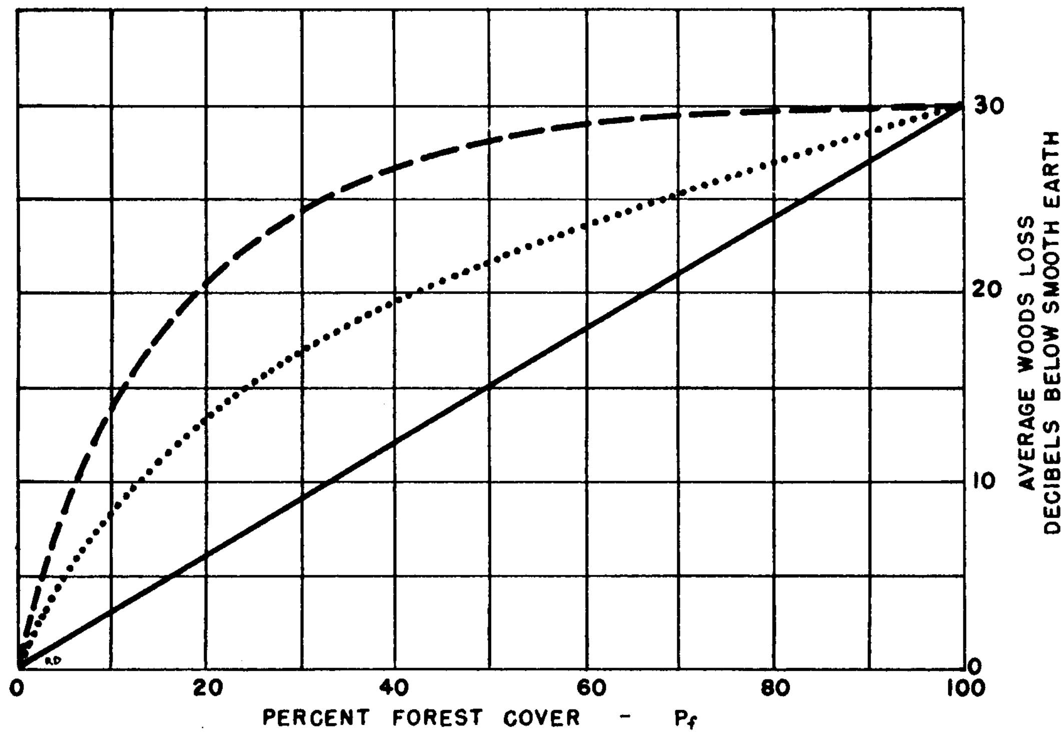

Figure 8

ESTIMATED AVERAGE SIGNAL DEPRESSION BELOW SMOOTH-EARTH VALUE AS A FUNCTION OF PERCENTAGE FOREST COVER P_f

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APPENDIX B

RADIO PROPAGATION IN URBAN AREAS

By
Anita G. Longley

RADIO PROPAGATION IN URBAN AREAS

Anita G. Longley[13]

This report reviews much of the earlier work on radio propagation in urban areas, including a good deal of data from measurement programs, careful studies of multipath propagation, and techniques to reduce multipath fading. A number of investigators have also developed propagation models for use in urban areas.

Most of these are largely empirical, and are presented as curves with various correction factors for antenna height, frequency and terrain irregularity. The present report describes a model, intended for use with a digital computer, which provides a rapid means for calculating both the median attenuation and the location variability expected in urban areas. The model has been tested against measured values and is applicable for a wide variety of conditions.

Key words: Broadcast systems; irregular terrain; land-mobile systems; location variability; radio propagation; urban communications.

1. INTRODUCTION

For many years land-mobile and broadcast services were concerned mainly with the lower part of the VHF band, but higher frequencies are now allocated, so for both broadcast and mobile systems we must consider frequencies up to 1000 MHz.

The random selection of receiver locations for these systems results in greater median propagation loss than would occur with selected sites, and also in greater path-to-path variability. Some irregularity in terrain causes an increase in field strength by breaking up the destructive phasing between direct and reflected radio waves that occurs over smooth terrain. However, as terrain irregularity increases, or as buildings and trees are added to the surface, the signal is reduced by shadowing, absorption, and scattering of the radio energy, and there is also an increased range of variation with location.

These effects of terrain irregularity, and of surface clutter, increase with increasing frequency. With the present trend toward the use of higher frequencies these effects become more and more important.

In land-mobile systems the antenna height on the mobile unit is low, usually not more than 3 m above ground. Between the base station and a mobile unit, and between the units themselves, an ever-changing and very large number of propagation paths are formed due to the motion from place to place. This multipath interference causes the signal to fade rapidly and deeply, and can be a serious problem in highly built-up urban areas where a large number of propagation paths may be formed.

In addition to the rapid, multipath type of fading, there is variability in signal level from one location to another. This may be referred to as path-to-path or location variability. In urban areas the location variability is highly dependent on the type and density of surface features, as well as on terrain irregularity, and radio frequency.

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The problems encountered in propagation in an urban environment contain too many unknown elements for complete theoretical modeling. For this reason data from measurements have been depended on in attempts to model radio propagation in urban conditions. Many such empirical models have been proposed, as indicated in Section 3.1. Of these several are presented in the form of curves of median field strength as a function of distance or range, with an allowance for path-to-path variability.

This report reviews much of the available data, considers techniques to overcome or control the rapid, multipath type of fading, and describes early and existing models for predicting median propagation loss and location variability. A model is described which takes into account the dependence of transmission loss on radio frequency, antenna heights, terrain irregularity, and distance, with an additional allowance for attenuation in urban areas as a function of surface obstacles and radio frequency. This model is developed for use with a digital computer and has been tested against available data.

2. SURVEY OF PREVIOUS WORK

Many measurement programs have been carried out to ascertain the effects of shadowing by terrain and by natural and man-made objects. Such shadowing may cause great attenuation of the radio signal and wide variation from one receiver location to another. The results of a number of such programs are described. Some studies of antenna height gain, the effects of differences in polarization, and the attenuation caused by trees are also discussed.

A serious problem in urban propagation is the multipath interference, which causes the radio signal to fade rapidly and deeply, depths of 30 dB being quite common. Many investigators have studied multipath fading, describing and analyzing its characteristics, and small scale statistics, with a view to developing techniques to limit or control this fading. Several approaches have been tried, including the use of directional antennas to reduce the number of reflected signals received, but probably a more useful technique is some form of space diversity. Much of this work on multipath interference and its control is referenced and discussed below.

2.1. Results of Measurement Programs

A great many measurement programs have been carried out to determine the effects of urban conditions on radio propagation. A number of these programs are discussed in this section, with significant numerical values listed in Table 1.

The effects of shadowing and multipath in an urban area were studied more than 40 years ago by Burrows et al. (1935). They measured the signal transmitted at a frequency of 34.6 MHz from the top of a high building, in the downtown area of Boston, to a mobile receiver. The received signal was quite variable, with an average value 12 dB less than that for a flat earth and a range of ±10 dB. They concluded that transmission under urban conditions may be considered in terms of transmission over level ground plus the wave interference patterns caused by reflections from the buildings, and an additional urban attenuation that is independent of path length. At about the same time measurements were made in Ann Arbor, Michigan by Muyskens and Kraus (1933). They obtained good coverage of Ann Arbor and environs with a signal at 58.8 MHz transmitted from a tower on the university campus. They obtained better results with vertical than with horizontal polarization. Jones (1933) reported observations at 44 and 61 MHz from the Empire State Building in New York. He reported the absorption through and around buildings as about 50% per 500 ft at 44 MHz and per 200 ft at 61 MHz. He also discussed reflection phenomena and interference patterns. During the same period Holmes and Turner (1936) made field strength surveys in the Camden-Philadelphia area at 30 and 100 MHz. They noted that the shielding effect of the thickly built-up downtown area of Philadelphia was very apparent, especially at 100 MHz, and that local conditions sometimes completely mask the relationship between terrain elevation and field strength.

Other early measurements reported by Goldsmith et al. (1949) showed that channel 5 signals in the streets of New York City were far below theoretical values and showed great variability in level, even though the terrain is essentially flat. They concluded that these effects were caused by the shadows and multipath reflections from the many high buildings. Brown et al. (1948) reported on measurements made in New York City at frequencies of 67, 288, 510 and 910 MHz from a transmitter atop the Empire State Building. A receiving van moved along two radials, one west over very hilly country through suburban areas with large houses and trees, and the other southwest over level terrain toward Princeton, New Jersey. They noted that shadowing by hills or other obstructions has a steadily increasing effect as frequency increases, and in hilly or obstructed areas multipath effects become severe at 510 and 910 MHz. On the smooth southwest radial outside of Manhattan there was little evidence of multipath, while along the other radial, especially in shadowed areas, signals arriving by many paths were numerous. As directional receiving antenna arrays were rotated, several positions were noted where strong signals were received, some as strong as the main signal. At the higher frequencies, multipath signals are profuse and the field may be badly distorted. In suburban areas over smooth terrain with many houses and trees, the median losses observed were 15 and 20 dB greater than calculated smooth earth values at 510 and 910 MHz, respectively. In these measurements, transmission from directional antennas at 510 and 910 MHz prevented multipath signals that would be caused by reflections from the buildings on Manhattan Island. High gain directive receiving antennas failed to function properly in shadowed areas where the field is distorted.

Kirke et al. (1951) conducted a mobile survey of field strength in the streets of London, with the transmitter at Wrotham, Kent. Transmission at 90.8 MHz from an antenna 220 ft above ground was received on mobile units with 20-ft antennas. They found that buildings of normal height in London reduced the average field strength by 10 to 12 dB, and also that the average for one street represented the average ±4 dB for the district. In a hilly and highly populated district the contours covered a range of some 34 dB. Local variations were much greater with vertical than with horizontal polarization, especially in the vicinity of trees. With vertically polarized radiation, the trees seemed to act as screening or absorbing agents rather than as reflectors, as the field strength tends to drop near trees.

In a series of mobile measurements in the Washington, D. C. and Baltimore areas, at frequencies of 71.75 and 94 MHz, Kirby and Capps (1956) compared the path-to-path variability in various surroundings. They noted consistently more variability at the higher frequency, with 10 to 90% ranges of 7, 13, 14, and 15 dB in overwater, wooded, urban, and farm areas, respectively, for distances up to 50 mi. These ranges correspond to standard deviations of about 3, 5.2, 5.6, and 6 dB. Glentzer (1956) performed tests at 450 MHz from four possible coverage stations in Chicago, Illinois. He observed the best coverage over a 30-mi. radius from the top of the Field building, about 575 ft above ground. He also noted that coverage is affected by the shadows of tall buildings, trees, and hills. Head and Prestholdt (1960) on analyzing a large number of measurements at VHF and UHF found much more variability of field strength values in rugged than in smooth terrain, and a much wider range of values in the higher frequency band. From a study of the variation of field intensity over irregular terrain, within line of sight, Fine (1952) reported that, for a distance of 5 to 30 mi., the median measured field strength at 400 to 600 MHz is 22 dB below that for a plane earth, with a standard deviation of about 12 dB. He also observed somewhat more variability at 910 MHz than at the lower frequencies.

Measurements were made by Aikens and Lacy (1950) at 150 and 450 MHz from a transmitter on top of the telephone building in New York City to mobile receivers. In Manhattan, city of skyscrapers, all measured values were 20 to 40 dB below calculated smooth-earth values. The mean excess loss was about 30 dB on cross-town streets but only about 15 dB on the north-south avenues. In suburban rolling country the excess loss was 5 to 40 dB, with a mean of 23 dB. On city streets, the variation over a distance of 200 to 400 ft was roughly 20 to 25 dB, while in open country it was only about half as much. In Manhattan and the Bronx, Young (1952) compared mobile radio performance at 150, 450, 900, and 3700 MHz. He concluded that for mobile radio telephone both 450 and 900 MHz are somewhat preferable to 150 MHz. At frequencies above 1000 MHz performance falls off because fluctuations in received signal level occur at an audible rate when the unit moves at normal speeds. For all frequencies the losses are about 30 and 20 dB greater than smooth-earth values for urban and suburban areas, respectively, with a 10 to 90% range of values of 25 dB in urban areas.

Studies by Epstein and Peterson (1953) and (1956) of transmission at 850 MHz in an urban area show the effects of different transmitting antenna heights. The radio signal was broadcast from station WOR in Jersey City and received at points along radials to the west and southwest through a heavily congested area, and through open country. At each receiving site the maximum field between 10 and 30 ft above ground was recorded. In the congested area over quite smooth terrain, within 13 mi. of the transmitter, the attenuation relative to free space was about 26 dB from a transmitting antenna height of 200 ft and only 15 dB when the height was increased to 740 ft. Similarly, about 14 to 20 mi. from the transmitter, in an area of open farmland with occasional woods and some buildings, the corresponding attenuations are 16 and 0 dB, respectively. They conclude that useful estimates of propagation loss can be made by calculating the free-space loss, the terrain shadow loss using knife-edge diffraction theory, and an additional factor which depends on the elevation of the transmitting antenna above suburban and rural areas. This attenuation factor depends on the angle of approach at the receiving antenna. This is the angle between an incoming ray from the transmitter and a tangent to the earth at the receivers. Attenuation is greater for low angle of approach since the path through intervening obstacles is longer. Based on an analysis of data at 67 and 850 MHz they define a "clutter loss" as a function of frequency and the angle of arrival of the signal.

(In this study the receiving antennas were 5 to 10 ft above housetops so the clutter loss does not include a dependence on the height of the receiving antenna.) For angles of arrival greater than 2^{o} the clutter loss is quite small but for smaller angles it becomes appreciable, more than 20 dB estimated at 900 MHz. Bullington (1957) reported that in New York City the median field for random locations at street level is about 25 dB below the corresponding plane earth value at 150 and 450 MHz, with a 10 to 90% range of 20 dB. Similarly, Nylund (1968) reported on mobile tests at 152.6 MHz in New York City and suburban areas. In the suburbs, the base station antenna was 80 ft high while in the city transmission was from a 205-ft antenna which was partially blocked by nearby buildings. The losses in excess of calculated smooth-earth values averaged about 11 and 36 dB in the suburban and urban areas, respectively. The statistical distributions of the depth and width of fades in rural, suburban, and urban areas are similar. The average fading depth was about 10 dB with 10% of fades reaching a depth of 25 dB, and a maximum of 35 dB.

The Federal Communication Commission (FCC) carried out a large measurement program to determine the usefulness of a UHF broadcasting station in the canyon-like city of Manhattan. The plan for this program was reported by Skrivseth (1961), data from mobile measurements along radials were listed by Hutton (1963), and the results of the program were described by Waldo (1963). Transmission from the top of the Empire State Building on channels 2, 7, and 31 (about 58, 178, and 576 MHz) was measured out to a range of 25 mi., with mobile surveys along radials to the limit of measurement. Tests were also made at nearly 4000 fixed locations, half of them in Manhattan within 5 mi. of the transmitter. The average attenuation relative to free space on unobstructed roofs within a range of 15 mi. was about 10 dB at all three frequencies. Comparison between reception at rooftop sites and with indoor antennas showed additional loss inside buildings in Manhattan of about 30 dB at the two lower frequencies, and 26 dB at the higher one. Outside of Manhattan the building penetration losses were about 5 dB less at all three frequencies.

Peterson (1963) discussed the results of the FCC measurement program with particular attention to the mobile surveys along radials. Along a radial over smooth terrain through a residential area, the average losses at all tested frequencies were 20 dB more than calculated smooth-earth values. A second radial over highly irregular terrain showed heavy shadowing by mountains but little "clutter" loss. He stated that the use of high-gain transmitting antennas has objectionable consequences in hilly terrain, and in a heavily built-up city area the receiving antennas are immersed in a sea of clutter, with no possible use of antenna directivity or gain.

Measurements at 836 MHz in Philadelphia, reported by Black and Reudink (1972), were from a 500 ft base station antenna to a van moving at 15 mi. per hr along streets in a small area in the central part of the city, and a larger area farther out. In the smaller area, variations of 20 dB or more were observed in the shadows of tall buildings, with a median path loss about 27 dB in excess of the calculated line-of-sight loss. In the larger area, where the buildings are more uniform in size, the median attenuation was about 17 dB, with an interdecile range of 13 dB. Changes in signal level with distance from 2 to 5 mi. show local mean values about 24 dB below free space, with a spread of some 30 dB. Near the transmitter, the variability is greater than it is farther away. Changes in local mean level depend on the terrain, the width of the street, sizes of buildings, and whether or not the transmitter is shadowed by tall buildings. They noted that the signal along radial streets is about 10 dB higher than on cross streets, even at a distance of 3 mi. from the transmitter. Measurements at 956 MHz from a base station 80 ft above ground in Washington, D. C., are reported by Deitz (1971). Signals received by a mobile unit fluctuate at a rapid rate, with fading amplitudes up to 40 dB. Along a narrow valley, Rock Creek Park, he observed about 5 dB more attenuation when the trees were in full leaf than during winter months.

Recently Barton and Wagner (1974) have reported mobile radio performance in urban, hilly terrain. They measured transmission loss at 455 and 862 MHz from a base station transmitter located on a bluff some 125 m high, in the central part of Pittsburgh. Measurements were made at Meadow Lands and at Harmarville, at distances of 32 and 16 km, respectively, over terrain with deep valleys and thick tree cover, the terrain having a peak-to-peak variation of 156 m. The average measured power received at 862 MHz was -107 and -97.5 dBm for the longer and shorter paths, respectively. This corresponds to an attenuation relative to free space of about 40 dB. Similar values were obtained at 455 MHz. They concluded that city-wide dispatch systems at 900 MHz will be practical not only in level areas but in hilly terrain as well. They also made measurements in long tunnels and under elevated roads which showed a remarkable improvement at 862 MHz over those at 450 MHz. They attributed this to more scattered signal illumination at tunnel entrances and multipath reflections along the tunnel walls at the higher frequency.

Extensive studies of land-mobile radio services in Japan have been reported by Okumura et al. (1968), and by Kinase (1969). Measurements at 200, 453, 922, 1310, 1430, and 1920 MHz, were made in the heart of Tokyo and its environs. Okumura et al. show the effects of "environmental clutter" in urban, suburban, and open areas for various frequencies, antenna heights, distances, and terrain types. They define an open area as clear for 300 to 400 m from the receiving antenna, a suburban area includes villages with scattered trees, and an urban area is a built-up city crowded with large buildings, two-story houses, and tall trees. (Until recently, the maximum building height in Japan has been 31 m.) Measured values of field strength in urban areas, over smooth terrain, are plotted versus path length for each frequency at several transmitting antenna heights with a 3 m receiving antenna. From these measurements they derived a set of curves of median attenuation relative to free space as a function of frequency for various distances in an urban area over practically smooth terrain. For a frequency range of 100 to 1000 MHz, the attenuation is 6 to 10 dB less in suburban areas, while in open areas it is 23 to 29 dB less than in an urban area. They note that the variability of the signal increases with frequency, and that there is less loss on radial than on cross streets.

Kinase (1969), reporting on measurements at 670 MHz in Tokyo and suburban areas, stated that in the heavily built-up central area of Tokyo the attenuation relative to free space is about 15 dB greater than in any other area. He reported median values of attenuation of 40, 30, and 25 dB in central urban, urban, and suburban areas. He calculated the effects of terrain irregularity to obtain a basic or theoretical field strength, and defined a clutter factor C as the ratio of observed to calculated field strength. This factor increases progressively with lower antenna heights, and with lower elevation angles, and is independent of terrain type. He noted that in suburban areas with large trees, C is comparable to that in built-up areas. Kinase defined a single parameter Γ as the area occupied by buildings, vegetation, etc., expressed as a percentage of the total area, in a unit area of 2 km^2. The clutter factor is then expressed as a function of elevation angle and radio frequency for each value of Γ. For example, in central Tokyo, $\Gamma = 50\%$, and the median clutter factors for a frequency of 700 MHz are about 22 and 32 dB at elevation angles of 0.055 and 0.008 radians, respectively. This parameter Γ can be used to describe clutter independent of such classifications as rural, small city, urban, etc.

Mobile measurements in other large cities have been reported by several investigators. In a large Russian city such measurements are reported by Trifonov et al. (1964) at frequencies of 50, 150, and 300 MHz. They observed deep fading with minima every half wavelength in the center of the city, about every wavelength at open sites within the city, and practically no interference fading at open sites outside of the city. The distribution of samples taken every half wavelength along city streets was lognormal in multilevel streets in the center of the city and Rayleigh in suburban areas, with intermediate Nakagami-Rice (Rayleigh plus a constant) distributions**.** They also observed less fading on wide streets and along radials than in streets.

Mobile measurements in Poland[14] at 158 and 306 MHz are reported from Warsaw, and from a town with a population of about 30,000. At 158 MHz in the heart of Warsaw attenuation due to urban clutter is 9 to 18 dB. At 306 MHz in suburban areas, 9 to 14 km from the transmitter, the attenuation is 12 to 21 dB, while in a small town it is about 10 dB. In another series of tests, signals received on a 30 m antenna in suburban and denser areas from a base station 1 to 6 km away, show clutter attenuations of approximately 5, 7, 10, and 13 dB at frequencies at 34, 46, 171, and 306 MHz, respectively.

Measurements on city streets in Italy[15] at 146 and 475 MHz from a mobile transmitter show that the additional loss in an urban environment depends on the density and heights of the buildings and on the vertical angle of arrival of the signal. These results are quite similar to those reported by Okumura from measurements in Japan**,** where the attenuation increases about 30 dB as the elevation angle is reduced from 4^o to nearly zero.

[14] Private communication

[15] Private communication

Measurements in West Berlin at 12 GHz are reported by Sakowski (1971). Transmission was with vertical polarization from three transmitting antennas at heights of 200, 95, and 56 m above average ground. He did not obtain adequate reception on 10 m receiving antennas but with 25 m receiving antennas the attenuation relative to free space for distances of 10 to 25 km was zero for 200 m height, 2 to 14 dB for 95 m height, and 10 to 25 dB for the 56 m antenna height.

Some of the results of these measurement programs are listed in table 1. Values shown in the table were for the most part recorded over smooth terrain and represent the attenuation caused by built-up urban and suburban developments at several frequencies. Some of the effects of irregular terrain will be considered in the section on propagation models.

In heavily built-up city areas we have seen that the additional loss may range from zero to about 40 dB, depending on frequency, antenna height, angle of arrival of the signal, and the density and height of the buildings. At frequencies from 40 to 250 MHz there is no great difference in signal level between urban and rural areas as long as the receiving antenna is above local roof levels, but with the receiving antenna at 10 m the additional attenuation in urban areas is 6 to 16 dB depending on the character and height of the buildings. At higher frequencies, 450 to 1000 MHz, urban attenuation may be from about 6 to 28 dB depending on the density and heights of the buildings.

2.2. Some Height Gain and Polarization Effects

In a land-mobile service, the receiving antenna is usually only about 3 m above ground, while for a broadcast service the height is about 10 m. The median height gain when the receiving antenna is raised from 3 to 10 m depends on the frequency. The CCIR (1-974d) reported that in the range 40 to 100 MHz the height gain is 9 to 10 dB in both rural and urban areas. For frequencies of 150 to 250 MHz the height-gain is 10 to 11 dB in urban or hilly areas, and about 7 dB in flat terrain. At 450 to 1000 MHz the height gain is 14 dB in urban areas and 6 to 7 dB in the suburbs, while in irregular terrain it depends on terrain irregularity, going from 10 to 0 dB as Δh increases from 10 to 500 m. (The parameter, Δh, is the difference in heights exceeded by 10% and 90% of the terrain in the range 10 km to 50 km from the transmitter.) At any specific location the actual height gain on raising the receiving antenna from 3 to 10 m may be quite different from these median values. As the receiving antenna is raised above surface obstacles a further height gain is to be expected. In an urban area, with receiving antennas above local roof levels no increase in transmission loss above that in rural areas is expected at frequencies below 100 MHz. In the 150 to 250 MHz band there may be an additional attenuation of 5 to 15 dB in urban areas depending on the density and height of the buildings and the angle of arrival of the signal at the receiving antenna. In urban areas in England an additional 9-dB attenuation was observed in the range 450 to 1000 MHz. When the receiving antenna is lowered from 3 to 1.5 m the additional attenuation is approximately 3 dB.

In both urban and suburban situations, increasing the height of the transmitting antenna may have a marked effect. The increased field can be related to the increase in elevation angle, as noted by Kinase (1969) and Epstein and Peterson (1953). The amount of attenuation should depend on the angle of approach at the receiving antenna, and should be greater for low angles of approach because the path length through intervening obstacles is longer. Another effect of raising the transmitting antenna is that this may elevate it above nearby obstructions, such as tall buildings, which may practically block out a whole segment, as noted by Black and Reudink (1972).

The directive gain patterns, polarization, and other characteristics of antennas are often greatly affected by the proximity of buildings and vegetation. In shadow regions at VHF the effect of reflections on vertically polarized signals is often sufficient to seriously distort FM reception, while they have little effect on horizontally polarized signals. Bullington (1957) noted that at 100 MHz the average loss from nearby trees was 5 to 10 dB with vertical polarization and only 2 to 3 dB for horizontally polarized signals. Such polarization differences were not observed at frequencies from 300 to 500 MHz.

Measurements in a hilly, wooded region near Detmold, Germany[16] at 97 MHz show the advantage of horizontal polarization in both field strength and quality of reception. The field strength was 5 dB higher and practically no reflections were observed with horizontal polarization.

Even at higher frequencies, Cunningham (1973) noted that small-sector signal variations at 900 MHz are greater for vertical polarization than for either horizontal or circular polarization. The received signal typically exhibits a variation of ±6 dB with vertical as compared with ±2 to 3 dB with horizontal or circular polarization.

When a transmitter is located at a clear site some discrimination against unwanted signals may be achieved by the use of orthogonal polarizations. In an urban setting, however, where multipath fading caused by scattering and reflection from buildings and trees is common, the resulting field is largely depolarized. Polarization discrimination exceeded at 90% of receiving sites is 20, 14, and 0 dB in flat, hilly, and mountainous terrain, respectively. With the transmitting antenna at a clear site the polarization discrimination at rooftop level in an urban area has a 90% value of about 9 dB (CCIR, 1974c). Some measurements at UHF indicate that there is slightly more depolarization for vertically than for horizontally polarized waves.

[16] Private communication

2.3. Attenuation by Trees

Many measurements have been made of the effects of forests and of individual trees on radio propagation. Typical dense, and rather extensive woods are practically opaque to radio signals at UHF and higher frequencies. The signal in the presence of woods near the receiving antenna appears to be principally that diffracted over the trees, but with less dense woods the signal transmitted through may be greater than that diffracted over them.

A small number of trees, or even a single tree, can cause considerable spatial variation in field strength at point within the shadow zone. When an antenna is placed in a grove of trees the signal is severely attenuated and the directive gain pattern, polarization, and other characteristics of the antenna may be strongly affected. Measurements made in jungles and rain forests by Herbstreit and Crichlow (1964) show that jungle attenuation of radio signals at VHF is very great, and that vertically polarized signals are attenuated about 15 dB more than horizontally polarized fields at a distance of one mile. Bergman and Vivian (1970) report measurements in jungles in the mountainous terrain of Panama. At about 50 MHz, for distances of 10 to 40 km, the average jungle loss was about 18 to 20 dB below free space, with a standard deviation of about 12 dB.

Large measurement programs have been carried out in tropical jungles, and the vegetation has been modeled as an imperfect dielectric slab. This so-called "slab model" represents the inhomogeneous, anisotropic, real jungle as an homogeneous, isotropic, lossy dielectric. (See reports by Pounds and La Grone, 1963; Hagn and Barker, 1970; Sturgill et al., 1967; Tamir, 1967; and others.) However, Vincent (1969) noted that scattering of VHF radio waves by trees is a significant factor, especially scattering by the tree trunks. He also measured values of the relative dielectric constant, ε, and conductivity, σ, for various frequencies. As the frequency is increased from 7 to 100 MHz ε decreases from 15 to 10 and σ increases from 3 to 20 mmho/m. As frequency is further increased, above 100 MHz, the trees tend to act more and more as individual scatterers, multi-path effects become increasingly significant, and there is much more radiowave attenuation than would be predicted by a "slab model". At VHF and UHF large attenuations are observed between antennas separated by a few hundred meters of trees. This attenuation is strongly frequency dependent, and is rather insensitive to tree density.

In urban areas we are concerned with the absorption, reflection, and scattering of radio energy by trees and other vegetation, and their effects on multipath near the receiving antenna.

Trevor (1940) measured attenuation through a patch of woods 500 ft thick at 500 and 250 MHz in summer and in winter. He observed strong standing wave patterns, with 3 to 4 dB more loss with vertical than with horizontal polarization. At 500 MHz the attenuations were 19 and 15 dB in the summer and winter, respectively, with vertical polarization. At 250 MHz the corresponding winter loss was 14 dB. The loss over 5 to 6-ft scrub pines was about 8 dB more than over a smooth earth. Sofaer and Bell (1966) also reported a foliage loss of about 4 dB at frequencies of 200 and 750 MHz in dense woods, with somewhat less loss through a single line of trees. Recently, Reudink and Wazowicz (1973) reported foliage attenuations of 10 and 20 dB behind a tree-covered obstacle at 836 MHz and 1-1.2 GHz, respectively.

La Grone and Chapman (1961) reported the effect of a single large oak tree on propagation at 2880 MHz. At distances of 300 and 900 ft from the tree the measured attenuations were 28 and 25 dB, respectively. These results agree with those of McPetrie and Ford (1946) which show a loss of 24 dB at a distance of 7 m behind the trunk of a large tree, at a frequency of 3260 MHz. They note that, at this frequency, trees in full leaf are practically as opaque everywhere as the tree trunk itself. Megaw (1948) reported measurements at 3260 MHz over a 37 mi. line-of-sight path, where a row of trees and houses near the receiver caused 25 dB attenuation below free space.

Saxton and Lane (1955) summarized the results of several sets of measurements in terms of rate of attenuation in dB per m of trees as a function of frequency. For trees in full leaf the attenuation rates range from about 0.05 to 0.5 dB/m as frequency is increased from 100 to 3000 MHz. The authors warn that this serves only as a guide to the order of magnitude, and that the rate of attenuation depends on many factors, such as the density of the woods. It should also be noted that these rates apply to situations where both antennas are in the woods.

Head (1960) considered the effects of thickets of trees between the path terminals, but with the receiver in the clear. Measurements at 485 MHz show that the signal is much attenuated near the woods, and that considerable clearing distance is required for recovery. He defined a clearing depth as the distance from the woods to the receivers. The signal then increases in proportion to the logarithm of the clearing depth, expressed in miles. At clearing depths of 0.01 and 1 mi. the corresponding attenuations are 35 and 12 dB.

A paper by P. L. Rice (1971) summarizes much of the previous work on the effects of vegetation. He notes that wetting the foliage increases its conductivity sharply, which tends to produce a depolarization of the overall field; and that the motion of trees causes depolarization fading of several decibels amplitude even with quite moderate winds.

In a recent paper La Grone (1977) reports measurements over a grove of trees at frequencies of 82, 210, 633, 1280, and 2950 MHz. The transmitter antenna elevations were 424, 148, 170, 225, and 225 m for each frequency, respectively, with path lengths of about 40 to 67 km. The grove of trees was about 9 m tall. The receiver was placed successively 4.5, 19.8, 35.1, 65.6, and 111.3 m behind the trees and the receiving antennas lowered from 18.3 to 1.5 m. The measured data show a better fit to propagation over an ideal knife-edge than that over a smooth spherical earth. At short receiver distances a significant amount of the signal energy propagates through the trees so that their effective height is less than their true height. This agrees with observations by Longley and Hufford (1975) of propagation to low antennas placed near, or within, heavy pine forests. They allowed for some transmission through the trees above the critical angle of internal reflection.

Assuming an effective dielectric constant ε for the woods, the critical angle θc, defined as

$$\mathrm{Sin}\theta_c = \varepsilon^{-1/2}$$

was about 110 mr or 6^o. This was then taken as the maximum allowable elevation angle at the receivers. The predicted values agreed well with measurements.

2.4. Multipath Fading

In a mobile radio environment the signal fades rapidly and deeply as a result of shadowing, multipath reflections, and scattering caused by terrain, buildings and trees. Fading depths of 30 dB are quite common. The fading rate is proportional to the radio frequency and the speed at which the vehicle travels. Increasing terrain irregularity and clutter cause increasing scatter and divergence or defocusing of the radio waves. Convergence or focusing and specular reflection also play a part in multipath phenomena.

Many studies have been made of the interference caused by multipath. Brooks (1965) analyzed the multipath interference to FM transmission of television between vehicles moving over a flat earth. Young and Lacy (1950), using short pulses at 450 MHz studied the echoes resulting from transmission from a land station to a moving car in lower Manhattan. Their results show delays ranging from -3 to +1.2 μs, with the greatest number from 1 to 3 μsec. In the interval 2 to 3 μs delay there is a 45% chance of a path within 12 dB of the main one, and an 18% chance of one within 6 dB. Such echoes may seriously limit the performance of wide-band radio systems.

Engel (1969) described the effects of multipath transmission on the propagation delay of a signal. Measurements of differences in propagation delay are used in automatic location of mobile units. If the signal is a pulse the receiver can detect the leading edge of the pulse and multipath does not impair the measurement. Engel described a procedure to determine the distribution of errors in measured values of propagation delay. Similarly, Figel et al. (1969) describe a method of vehicle location based on measurement of signal attenuation from a mobile transmitter. They developed an automatic sampler and totalizer for this purpose.

In measurements at 836 MHz in New Providence, N. J., Lee (1966) and Stidham (1966) observed a marked reduction in fading rate using a directional antenna on the mobile unit. Increasing the antenna directivity further reduced the fading rate, at a distance of about 2 mi. with an average attenuation of about 33 dB below free space. Antenna orientation had little effect on the average signal level, but the minimum fading occurred along and at right angles to the direction of motion and in the direction of the base station.

Many studies have been made of the characteristics of multipath. Some of these deal with the statistics of time-domain representations of multipath propagation in a mobile radio environment. For some applications such descriptions are convenient, but in other cases frequency-domain descriptions such as frequency correlation functions and correlation bandwidths are more useful. In the time domain we consider Doppler shifts, time delays, and crossing rates. Reudink (1.972) noted that fading rate is proportional to vehicle speed and frequency with minima occurring at about half wavelength spacing. The rate of fading and crossing rate is the same for urban and suburban streets, and for those parallel to and perpendicular to the transmitter in New York City. In a later report, Reudink (1974) describes the amplitude variation of the signal envelope as Rayleigh distributed when measured over distances of a few 10's of wavelengths, with statistically independent phases from zero to 2Π. The vehicle motion introduces a Doppler shift in every wave and the received frequency differs from that transmitted by an amount

$$w_n = kv \cos\alpha_n$$

where $k = 2\pi/\lambda$, λ is the radio wavelength, v is the velocity of the mobile unit and α_n is the angle between the incoming wave and the direction of motion. The Doppler shift is bounded by +/- kv which is much less than the carrier frequency. For example, at 1000 MHz, with a vehicle traveling 96 km/hr the Doppler shift w_n is 560 Hz. At much higher frequencies the Doppler shifts maybe well within the audio band. Signals arriving by various paths may be shifted by different amounts producing a beat between them.

Cox (1972a,b) described small-scale statistics of time delays and Doppler shifts associated with multipath propagation in a vehicle traveling along suburban streets. He notes that while the distribution of signal amplitudes at fixed delays is usually Rayleigh this is not always the case. For Doppler shifts associated with scattered fields arriving from different angles, multipath characteristics can be obtained by measuring the complex bandpass impulse response as a function of distance along them direction of travel. These measurements yield delay Doppler power profiles (scattering functions), average power delay profiles (power impulse responses), and correlation of transfer function fluctuations as a function of frequency separation. These parameters set bounds on system performance parameters such as FM-distortion, adjacent channel interference levels, error rates in digital systems, the effectiveness or some diversity systems and the accuracy of vehicle locating systems. His measurements in Middletown, New Jersey, at 910 MHz showed excess power delays of 6 or 7 μs and delay spread of about 2 μs. In suburban residential and commercial areas in relatively flat terrain the delay spread is usually less than 0.25 μs. Cox (1973) reported that measurements in New York City at the same frequency showed excess time delays of 9 to 10 μs with delay spreads of 2 μs. He describes an urban mobile radio channel as a Gaussian quasi-widesense stationary uncorrelated scattering channel within a 10 MHz bandwidth and for intervals along the street of up to 30 m. Usually for intervals of more than 50 to 100 m along a street the multipath scattering process becomes grossly non-stationary.

Bello (1963) has shown that time and frequency-domain descriptions are related through Fourier transforms, frequency-domain descriptions can be obtained directly from time-domain measurements. He suggests that time-varying linear channels may be characterized in a symmetrical manner by arranging system functions in time and frequency pairs. For example, he considers a widesense stationary channel in terms of channel correlation functions. Jakes and Reudink (1967), considering the envelope of the received signal as a bandlimited time-varying functions obtained power spectra by taking the Fourier Transform of the autocorrelation function. The spectrum cutoff occurs at the expected value of $2v/\lambda$ Hz. Below this frequency the energy is approximately uniformly distributed.

Bello (1971) relates multipath and frequency-selective fading caused by scatter phenomena to the statistical spatial characteristics of the refractive index. When multipath causes distortion he suggests that the scatter portion of the channel be modeled as a continuum of uncorrelated scatterers.

Schmid (1970) described a model to predict the probability distribution of direct path and multipath received signal power. He calculated the probability of occurrence of distinct multipath propagation of pulse signals over irregular terrain, and with an irregular distribution of obstacles such as buildings. Pulse communication systems are generally tolerant of multipath propagation that produces a reflected pulse whose delay is small compared to the pulse width. If delays are sufficient to pose a potential problem, their amplitudes will generally have to fall within a certain range of the amplitude of the direct path signal before system degradation results.

Turin et al. (1972) performed measurements in the San Francisco Bay area with the simultaneous transmission of 100 ns pulses at 488, 1280, and 2920 MHz received at a mobile van. They state that most data are by CW techniques and show fading distributions useful for narrow band systems but are of little use for analysis and design of wide-band systems, which use as much as 10 MHz bandwidth for some radiolocation systems. They consider that the propagation medium acts as a linear filter and consider the impulse response to this filter. The procedure requires absolute timing for radiolocation techniques, and they used stable, synchronized, and calibrated atomic clocks at both transmitting and receiving terminals to obtain the statistics of excess delays. The model assumes that the carrier phases of the various paths are mutually independent and uniformly distributed over the range zero to 2π. The statistics of path delays and strengths are then needed to describe the propagation medium. They assume that path strengths over local areas have a Rayleigh or Rice distribution, while over larger areas they are lognormal, and that path delays form a Poisson sequence.

Ossanna (1964) described a model for mobile radio fading based on the geometry of reflections from randomly placed vertical plane reflectors. He noted that the detailed shape and especially the sharp cutoff frequency of spectra depend critically on the angle between the direction of vehicle motion and the direction to the fixed station. As the angle increases from 0^o to 90^o the cutoff frequency falls from about 37 to 20 Hz. Clarke (1968) developed a scatter model in contrast to Ossanna's reflection model. This scatter model assumes that the incident field is composed of randomly phased azimuthal plane waves of arbitrary azimuthal angles. Amplitude and phase distributions, spatial correlations, amplitude spectra, and frequency correlations of the received signal are deduced. In urban areas the amplitude for a short run is Rayleigh distributed which implies that there is no significant direct component and the fields are entirely scattered. In towns and woodlands the distribution may be Rice or non-zero-mean Gaussian, indicating a significant direct component wave. The spatial correlation of the field components is derived from the probability density function $p(\alpha)$ where α is the angle between an input component wave and the vehicle. The spectrum is derived from $p(\alpha)$ and $g(\alpha)$, the azimuthal gain of the antenna, and the coherence of two radio frequencies is derived from $p(\Delta t)$ the probability of time delays. The model then describes mobile radio fields in terms of $p(\alpha,\Delta t)$.

A knowledge of the fine structure of the radio field can be useful in determining ways to offset destructive fading. For instance, Gilbert (1965) derived statistical properties from mathematical models of multipath fading, which include energy density distribution functions. He points out the advantages of receiving from a vertically polarized transmitting antenna on three antennas, a vertical dipole and a pair of loop antennas whose axes are perpendicular to each other and to the dipole. These receive the three field components E_z , H_x , and H_y, which are added to obtain the total energy density. Lee (1967) noted that using an energy density antenna the signal fades only about half as often as the electric field and the fades do not last as long. (The antenna receives the three field components simultaneously, and summing the squares of these signals gives an output proportional to the energy density.) Several other ways to reduce fading effects are discussed below.

2.5. Diversity Techniques

The depth of fading can he reduced by spatial diversity and predetection combining. Rustako (1967) noted that multipath fading is greatly reduced using a predetection combining receiver in four branches. Tests were made at 836 MHz in a mobile van moving at 15 mi per hr in New Providence, using a single channel and two, three, and four-channel diversity. The receiving antennas were one-fourth wavelength vertical whips with antenna spacings of 1/4, 3/4, and 5/4 λ. In all tests there was increasing improvement with increasing diversity. With four-channel diversity the fading was reduced from 30 dB to 10 dB fades for 0.1% of the distribution. Rustako et al. (1973) compared two types of predetection switching space diversity systems at 840 MHz with vehicle speeds at 80 mi per hr. The first type was conventional receiving antenna switching with a single transmitting antenna. The second type was a feedback diversity system with single receiving antenna and two transmitting antennas which were switched by remote control from the receiver. The differences in performance were due primarily to the time delay inherent in the remote antenna switching. Parsons, et al., (1973) suggest the use of a single receiver diversity system, with predetection combiner incorporated into the receiver design, using a 3-element self-phasing antenna array. A later paper, Parsons et al. (1976), discusses the nature of the electromagnetic field in urban environments and surveys a number of diversity techniques as applied to mobile systems. The authors conclude that diversity at the mobile receiver appears to be preferable to diversity at the base station.

Bitler et al. (1973) describe a system to provide two-way diversity with diversity combining done at the base station. The mobile transceiver is very simple, while at the base we have a multiple branch diversity receiver and diversity transmitter. Jakes (1971) noted that relatively modest use of diversity can afford savings in transmitter power of 10 to 20 dB. Such savings may be achieved using receiver diversity with either selective or maximum ratio combining of two to four branches, with selection giving somewhat better performance. The advantages of transmitter diversity are for larger bandwidths and generally are not as great as for receiver diversity.

Lee (1973) studied the correlation between signals received on two base station antennas to determine the spacing required for diversity. He noted that propagation in the direction of a line connecting the two antennas is the critical case, and requires a large separation of about 70 λ. When the incoming wave is as much as 15^o away from the in-line axis the required spacing drops to 30 λ. Local scatterers near the base station tend to decrease the correlation between signals at the two antennas, and when the correlation is less than 0.7 most of the advantages of dual diversity are obtained. In a built-up, urban area, where the base station is surrounded by tall buildings, the correlation is expected to be low.

Arredondo and Smith (1977) discussed diversity and vehicle speed as they affect fade durations on voice transmission, and bit-error probability for data systems.

Different base stations in a mobile radio system transmit different signals simultaneously, at the same frequency, to mobile vehicles in their respective areas or "cells". As a vehicle moves, both desired and interfering signals show local deep fading so that at times the undesired signal may be the stronger. Schiff (1972) described the use of additional antennas to provide independently fading signals. He considered three different switch diversity techniques to avoid interference.

3. PROPAGATION MODELS FOR URBAN AREAS

Many investigators have tried to develop ways to predict median values of propagation loss in built-up areas, where buildings and trees may cause severe attenuation of the radio signals. Others have been concerned with describing path-to-path variability and multipath fading in statistical terms.

3.1. Existing Propagation Models

When we consider the median path loss in urban areas, we find that many investigators calculate first the propagation loss to be expected if the buildings and other surface features were not present. The additional observed loss is then assumed to be caused by the urban, or suburban, development. Over rather smooth terrain, such as we find in Manhattan, theoretical plane earth values have first been calculated. The differences between these and the measured values have then been variously referred to as the shadow loss, excess loss, urban factor, clutter factor, etc. In a similar manner some investigators have compared measured losses with calculated free space values.

An early model by Bullington (1947) describes a simplified method for calculating propagation over a smooth spherical earth, with empirical allowances for the effects of hills and buildings. In a later report, Bullington (1950) described a "shadow loss" as a function of frequency and terrain irregularity, which is added to theoretical "plane earth" values. This shadow loss increases from 0 to 35 dB as a parameter $(H/\lambda)^{1/2}$ increases from 0 to 26. Here λ is the wavelength, and H is the difference in elevation between the lowest point on a path and the elevation required to provide line-of-sight conditions. In discussing the effects of buildings and trees he noted that in the range 40 to 450 MHz in Manhattan the median loss at street level is 25 dB greater than the plane earth value, with 50 to 90% range of 10 dB. For trees and other objects he found the shadow loss to be small, but it increases with increasing frequency.

Egli (1957) used available data to develop empirical formulas, which he presented in the term of nomograms and correction curves. The basic model is the theoretical plane earth field to which he added a "terrain factor" that depends on frequency but not distance, and an estimate of location variability.

Sets of propagation curves have been developed by the International Radio Consultative Committee (CCIR) and by the US Federal Communication Commission (FCC). The CCIR (1974a) curves for broadcasting services are presented in Recommendation 370-2. These show field strength as a function of distance for various frequency ranges, with correlation factors for terrain irregularity, and estimates of location variability. The FCC curves, reported by Carey (1964), were derived from certain of the CCIR curves, with adjustments for antenna heights. These curves of field strength versus distance were adjusted downward by 9 dB to allow for the low receiving antenna heights. The curves for various transmitting antenna heights assumed a linear height gain within line of sight and are blended into the transhorizon values. Damelin and Daniels (1965) reported some modification in the FCC curves.

Burroughs (1966) compared measurements in urban areas with those in jungles. He concluded that the additional attenuation observed in both cities and jungles is frequency sensitive, but its average value is independent of both antenna height and path length. When the terrain is irregular additional problems are encountered, as some allowance must be made for terrain effects. Epstein and Peterson (1953) suggest that useful predictions of propagation can be made using the calculated free-space field reduced by knife-edge shadow loss in hilly areas, and certain "experience factors" which are functions of transmitting antenna heights in congested suburban and rural areas. Later the same authors, Epstein and Peterson (1956) noted that received field strength is a function of surface clutter around the receiving site, unless the receiving antenna is above the clutter. They therefore defined a "clutter loss" as a function of angle of arrival of the radiation at the receiving site, and the frequency, assuming a linear frequency dependence. Based on the analysis of data at 67 and 850 MHz they define this clutter loss for antennas 5 to 10 ft above housetop levels. La Grone and Chapman (1961) also noted that the elevation angle toward the transmitter has a marked effect on the attenuation caused by a solid grove of pine trees. Reudink and Wazowicz (1973) calculated knife-edge diffraction to predict the loss over a tree-covered hill. The measured loss was about 10 and 20 dB greater at 836 MHz and 11.2 GHz, respectively. They suggest predicting coverage from a base station using knife-edge diffraction plus a factor for foliage. Deygout (1966) suggested calculations of multiple knife-edge diffraction to estimate the effects of a series of hills or ridges.

Gilbert (1975) describes a simple model for line-of-sight paths over random terrain. He considers all terrain irregularities as composed of conical hills, all the same heights distributed randomly over a spherical earth. He then assumed that a base station is located at the peak of a hill and calculated horizon distances, coverage area, and the probability that a random point at ground level is within line of sight of a peak at a specified distance. Neham (1974) compared several propagation models and finally chose a coverage prediction model based on the plane earth formulation described by Egli (1957) but his modification allows for irregular terrain in terms of a factor for location variability.

A somewhat different approach is taken by a group of Japanese investigators. Okumura et al. (1968) used an extended series of measurements in Tokyo and its environs to develop a series of curves of median attenuation relative to free space as a function of frequency at various distances. These curves, shown in Figure 1, are for an urban area in almost smooth terrain with antenna heights h_{te} = 200 and h_{re} = 3 m. This basic prediction can then be modified by a series of correction factors to obtain a prediction for the required situation. Correction factors relating to suburban and open areas, different antenna heights, vertical angle of arrival of the signal, orientation of the street, and terrain irregularity, are given.

Kinase (1969) introduced a parameter I' to represent the effects of environmental clutter in the vicinity of a receiving site. He calculates a reference value using theoretical values for a smooth spherical earth, single and multiple mountain ridges, cliffs, and rounded and rectangular objects. This calculated theoretical value is then compared with the observed field to obtain a clutter factor C which is independent of terrain, and describes the additional attenuation caused by buildings and trees. The clutter factor is sensitive to differences in urban structure, in frequency, and in angle of elevation. The parameter Γ expresses the area occupied by buildings, vegetation, etc. as a percentage of the total area in a unit of 2 sq km. Figure 2 shows median values of C as a function of elevation angle for frequencies of 150 and 750 MHz and values of Γ from 1 to 50%. Figure 3 shows median values of C as a function of frequency at a constant elevation angle of 0.005 rad for values of Γ from 1 to 50%.

While Kinase (1969) observed that lowering the receiving antenna from 10 m to 4 m had little effect on location variability in rural and suburban areas, one would expect greater variability at street level than on rooftops in an urban area.

A study by Dymovich (1959), which reviewed the results of early measurement programs and prediction models, suggested that field strength in towns be predicted as a function of the radiated power, the product of the antenna heights, and the reciprocal path with two coefficients to be determined by data, he noted that measured values of field strength are lognormally distributed, and that measurements in Leningrad at 45 MHz, with receiving antenna heights of 5.2 and 8.2 m show the same location distribution, with a 10 to 90% range of 6 dB.

Palmer (1976) reviewed much of the work on propagation in land mobile systems in the 470 to 890 MHz frequency range. He considered a number of propagation models that are currently in use. These have all been developed to fit measured data, and are expressed as functions of frequency, antenna heights, and distance, with allowances for path-to-path variability. Neham (1974) in a similar comparison of existing models noted that the various models give similar results in predicting coverage ranges for 90% of the receiver locations. For this 90% comparison he used location variability factors of 11, 14, and 17 dB in the frequency bands 25 to 50 MHz, 150 to 1170 MHz and 450 to 470 MHz, respectively.

Allsebrook and Parsons (1977) report the results of measurements in three British cities, Birmingham, Bath, and Bradford. The median attenuation relative to plane earth values was 16, 18, and 35 dB at frequencies of 86, 167, and 441 MHz respectively. This urban attenuation was not dependent on distance for a range of 1 to 10 mi, but was strongly frequency dependent. They suggest a model for predicting propagation loss to mobile receivers as the sum of plane earth loss plus diffraction loss over obstacles plus a correction factor for UHF. For a hilly city, such as Bradford, they use an additional term to allow for the effects of hills.

In a recent paper Bullington (1977) presented a series of nomograms for the ready calculation of free space, plane earth and diffraction losses. He commented that buildings are more transparent to radio waves than the earth is, so they should not cause as much attenuation as hills. On the other hand the artificial canyons caused by buildings in cities are much narrower than naturally occurring ones, which would increase the attenuation. At higher frequencies, about 1000 MHz, if trees block one's vision they are equivalent to solid obstacles.

Durkin (1977) reports a prediction model used for frequency assignment procedures for the land-mobile services in the United Kingdom. This model combines values from the CCIR (1974a) curves within line-of-sight with values calculated using the Longley and Rice (1968) model for transhorizon paths. The latter is used, with digitized terrain elevations, to calculate the attenuation to a large number of points along 72 equally spaced radials from the transmitter. Field strength contours are then drawn to show the predicted service area. He gives a comparison with measurements made at 85 MHz along one of these contours from a transmitter base in Barkway, Hertfordshire.

The various models described above have been used to estimate median attenuation in urban areas. There is also considerable variation from path-to-path about this median value. Estimates of path-to-path or location variability are based on the results of measurements, which show that the variability is log-normally distributed with a standard deviation that ranges from about 5 to 20 dB depending on the radio frequency, type of terrain, and whether the lower terminal is in open or cluttered surroundings.

Saxton and Harden (1954) reported measurements at 593.6 MHz which showed 10 to 90% ranges of 19 to 34 dB. Location variations over short distances showed smaller ranges of 2 to 4 dB at open sites, 8 to 10 dB with isolated trees and buildings, and 15 to 20 dB in a built-up area with trees and large buildings.

Report number 228, CCIR (1974b) describes a variation factor, V (50 to 90% of locations) for towns in the United Kingdom. In 121 towns at frequencies from 700 to 1000 MHz the median location variability V was 9.8 dB, while in 40 towns at 250 MHz the observed median V was 7.7 dB. These correspond to standard deviations of approximately 7.8 and 6.2 dB for the higher and lower frequency hands, respectively.

Okumura et al. (1968) observed a gradual increase in location variability with increasing frequency, the standard deviation increasing from 5 to 8 dB, and from 6.5 to 10 dB as frequency increased from 100 to 3000 MHz in the smooth urban area of Tokyo, and in the hilly suburbs, respectively. However, in highly built-up urban areas the variability may be much greater. Waldo (1963) reported standard deviations of 16, 17, and 18 dB at frequencies of 57, 177, and 576 MHz at rooftop receiving antennas in Manhattan.

Reudink and Wazowicz (1973) observed that location variability in Holmdel, New Jersey, increased with increasing distance from a base station to standard deviations of 15, and 18 to 20 dB at 836, and 11,200 MHz, respectively, at a distance of 12,000 to 18,000 ft. Neham (1974) suggests that in an urban area location variability factors of 11, 14, and 17 dB be used for frequency ranges of 25 to 50, 150 to 170, and 450 to 470 MHz to estimate 90% values. These would correspond to deviations of about 9, 11, and 14 dB for these three frequency ranges. The CCIR (1974c) recommends that location variability at frequencies from 450 to 1000 MHz should include an allowance for terrain irregularity. They show standard deviations of 10, 15, and 18 dB for rolling, hilly and mountainous terrain, respectively, in this frequency range.

Several investigators have shown that location variability increases with increasing frequency. This relationship has been expressed mathematically in terms that agree fairly well in the lower VHF range but give estimates of standard deviation that differ by more than 10 dB at 1000 MHz. A recent report, Longley (1976), summarizes much of the earlier work, and describes location variability as a function of the parameter $\Delta h/\lambda$, where λ is the radio wavelength and Δh is a measure of terrain irregularity. This relationship was developed from data that were obtained largely in non-urban areas.

3.2. A Computer Prediction Model

Some of the parameters that have been shown to be important in urban propagation are: the radio frequency, the heights of buildings and trees relative to the height of the receiving antenna, the distance from the receiving antenna to the nearest obstacles, the uniformity and density of surface structures, and the possible absorption of radio energy by such obstacles.

Since the distribution and shape of clutter surroundings is quite irregular we must consider the problems on a statistical basis. The transmitting antennas for broadcast services, and the base station antennas for mobile systems, are usually well elevated above the buildings and trees, so we may consider the dominant factors influencing propagation to homes and mobile units to be (a) terrain irregularities along the transmission path, and (b) the urban or environmental clutter near the receiving site. If, however, the transmitting antenna is not elevated well above surrounding buildings, some attenuation results from interference to the direct transmission path, and nearby buildings could block out whole areas from adequate service.

A propagation model for computerized predictions of transmission loss over irregular terrain, developed by Longley and Rice (1963), is applicable to broadcast and mobile services. This model is based on propagation theory, and has been compared with measurements for a wide range of frequencies, antenna heights, terrain types and distances. Several small modifications have been made since the development of the original prediction model. Some of these have simplified certain computations, or increased the efficiency of computer programming. But, recently, changes have been made in the original formulation of the model in the line-of-sight region. These changes are described in the appendix to this report. They provide better agreement with both theoretical and measured values, especially at UHF with one antenna elevated, than was obtained with the original method. The propagation model calculates transmission loss, with allowances for radio frequency, terrain irregularity, path length, and antenna elevations.

Most of the data previously considered were from open areas, towns and small cities. To this model we can now add an allowance for the additional attenuation due to urban clutter near the receiving antenna. This allowance is a function of radio frequency, distance from the transmitter, and probably the density of urban clutter. To estimate this allowance, a comparison is made with curves through measured values.

Some of the most widely used prediction curves that were drawn through measured values are those of International Consultative Committee (CCIR), the U. S. Federal Communication Commission (FCC), and those derived by Okumura et al. (1968) and shown Figure 1. These are all empirical curves, based on measurements, and are to a considerable extent interrelated. The curves shown in CCTR Report number 567 (1974d), and intended for the land-mobile services at 150 MHz, are obtained from the curves in CCIR Recommendation 370 by adjusting the receiving antenna height from 10 m down to 3 m, an increase in attenuation of about 10 dB. The CCIR 150 MHz curve, with h_1 = 200 m and h_2 = 3 m, for rural conditions, shows about 3 dB less attenuation than the corresponding Okumura curve, for urban conditions. The CCIR curves at frequencies of 450 and 900 MHz for an urban are taken directly from the basic Okumura curves, with 3-dB additional attenuation for a receiving antenna height of 1.5 m instead of 3 m. The FCC curves, in turn, were derived in part from the CCIR curves shown in Recommendation No 370 (1974a) assuming a linear height gain within line of sight and blending into the transhorizon region.

Because these prediction curves have been widely accepted, and are interrelated as shown, we compared values of attenuation relative to free space calculated for non-urban areas using the modified Longley-Rice computer model, with those read from Okumura's curves, Figure 1, for an urban area. For both models we assumed rather smooth terrain with effective antenna heights of 200 m and 3 m. Values were obtained for frequencies from 100 to 3000 MHz, and for distances up to 100 km. As expected, the Okumura urban curves show greater attenuation. The differences between the two models may be considered as representing the additional power loss in an urban area, and referred to as an "urban factor". The values listed in Table 2 show this factor for each frequency and distance. The urban factor, UF, increases smoothly with increasing frequency, and decreases with increasing distance from the transmitter. With frequency in MHz and distance in km this relationship can be expressed quantitatively as

$$UF = 16.5 + 15 \log(f/100) - 0.12d \text{ dB}, \quad (1)$$

with an error of less than 1 dB at all frequencies, to a distance of 70 km. At frequencies greater than 500 MHz and distances greater than 70 km this relationship tends to over-estimate the loss, because the attenuation decreases somewhat more rapidly with distance in this range.

Comparisons were also made between the two models at frequencies of 150 and 450 MHz with transmitter effective heights of 30, 50, 100, 200, 600, and 1000 m. The differences between Okumura and Longley-Rice predictions show little change with height as the height is increased from 30 to 600 m.

This computer prediction model, with the urban factor added, should adequately predict the median attenuation for moderately large cities in rather smooth terrain. The median attenuation is calculated as a function of distance for a desired frequency, antenna heights, and degree of terrain irregularity in both urban and non-urban areas.

Table 2. Urban Factor: A(Okumura)-A(Longley-Rice) dB

d km	100	150	200	300	500	1000	2000	Frequency 3000 MHz
10	16.2	17.4	20.6	22.9	26.6			
20	13.4	15.9	18.2	20.6	24.1	29.4	36.3	
30	11.5	14.3	16.4	1.9.1	22.7	27.4	34.0	38.3
40	10.9	13.4	15.3	17.9	21.5	26.0	31.9	35.7
50	10.0	12.8	14.8	17.5	20.7	25.3	30.7	34.2
60	9.3	12.1	13.5	16.4	19.4	24.0	29.1	32.2
70	8.6	11.2	12.8	15.3	18.2	22.5	26.2	28.8
80	8.0	10.6	12.0	14.2	16.4	20.0	22.7	24.3
90	7.3	9.4	10.7	12.0	13.8	16.9	18.5	19.4
100	6.5	7.7	8.3	10.0	11.2	13.5	14.1	15.2

h_1 = 200 m, h_2 = 3 m

There is also a place-to-place or location variability to be considered. As described in an earlier report, Longley (1976), the standard deviation, σ_L **,** of this location variability is a function of frequency and terrain irregularity. For data from non-urban areas, with randomly located receiving antennas, this relationship is expressed as

$$\sigma_L = 6 + 0.55f(\Delta h/\lambda)^{1/2} - 0.004(\Delta h/\lambda) \text{ dB}, \qquad (2)$$

where Δh is the terrain irregularity and λ is the radio wavelength. In smooth to slightly hilly terrain the frequency dependence is

$$\sigma_L = 5 \log f - 1 \text{ dB} \qquad (3)$$

for frequencies $\geq$ 10 MHz. This is more variability than that observed by Okumura in Japan but agrees with the relationship shown by Egli (1957).

To determine the service area of a station, a simple area prediction of transmission loss as a function of distance may be used as described above. However, if the terrain in an area is not homogeneous, the computer model may be used to compute attenuation from point-to-point along a large number of radials from the transmitter. When digitized terrain elevations are available the profile along each radial is calculated. With this information field strength contours can then be drawn to show in detail the predicted service area. Durkin (1977) describes using the Longley-Rice (1968) model for this purpose in automated frequency assignment procedures in the United Kingdom.

4. SUMMARY AND CONCLUSIONS

This paper has reviewed much of the earlier work on urban propagation including the results of measurements by many investigators, and a number of models developed for predicting trans-mission loss in urban conditions. Some of the more important propagation parameters have been identified. A computerized model is described in Section 3.2 for predicting median attenuation as a function of distance and for determining the service area of a transmitting station, in an urban area. Equations also given for calculating the location variability as a function of frequency and terrain irregularity, or for rather smooth terrain as a function of frequency alone. This computer model provides a ready means for determining the service area of a transmitter for broadcast and mobile services. However, a number of questions remain, and further analysis and development are desirable.

For example, most of the urban data are from areas where the terrain itself is rather smooth. What happens in a city where the terrain is hilly? Would this modify the "urban factor"? A limited amount of data indicates that this may indeed be the case. Measurements made in Pittsburgh by Barton and Wagner (1974) were compared with the Longley-Rice (1968) area prediction. The measurements at 455 and 862 MHz were made over 2 paths at distances of 16 and 32 km. For the shorter path the terrain parameter Δh = 185 m and for the longer one Δh = 116 m. This represents quite hilly terrain. For these paths the computed attenuation agreed well with the measured values with no addition of an urban factor. This would suggest that the urban factor is also a function of terrain irregularity and decreases as the terrain becomes more irregular. Further study, including point-to-point predictions along the two profiles, would help to clarify this question.

It would be of considerable interest to pursue the question of the effects of elevation angle at the receiving antenna. This would require a knowledge of the heights of buildings and trees relative to the height of the receiving antenna, and the distance to the nearest obstacles. When the angle is low the ray path through the surface clutter is long, causing considerable attenuation, but as the elevation angle is increased the attenuation decreases rather sharply as the path of the radio ray rises above the clutter. This suggests a possible critical angle above which the radio energy is diffracted over and around the surface obstacles.

We have tended to emphasize the effects of buildings and trees near the lower, or mobile, antenna. With very high transmitting antennas this is probably the most important effect, but with antennas only 50 to 80 m high the proximity of very tall buildings has a marked effect. Recent measurements show field strength values some 15 dB lower from a transmitter in an urban area than from one in a suburban or residential area to receivers in similar surroundings (Kozono and Watanabe, 1977).

In a highly built-up area, such as parts of Manhattan, a general propagation model, such as that described in Section 3.2 of this report, cannot allow for the differences observed along radial and cross streets, and for areas that are screened by very tall buildings. Such problems would require special treatment including consideration of the specific situations involved.

Table 1. Summary of Measured Values

Reference	ht ft	d mi	f MHz	Median A in dB	10-90% range in db	Description of Area
Burrows et al. (1935)		4-10	35	12*	20	Boston
Fine (1952)		5-30	400-600	22*	28	Summary of a number of US measurements
Brown et al. (1948)	1300		288	(little attenuation)		NY suburban, with many
			510	15*	20	houses and trees over
			910	20*	30	smooth terrain
Aikens and Lacy (1950)	460	3-11	150 & 450	30*	20	Manhattan, crosstown
				15*		Manhattan radial
		13-26		23*	35	hilly, suburban
Bullington (1950)			150 & 450	25*	20	Manhattan
Waldo (1963)	1300	15	58	10		New York City, at rooftop
			178	10		levels
			576	10		
Young (1952) 460		<10	150	24*	25	Manhattan and the Bronx
			450	30*		
			900	25-40*		
		>10	150	12*	25	Suburban NYC
			450	20*		
			900	24*		
Epstein and Peterson (1953)	740	0-13	850	15		Urban, Jersey City
	560			16		heavily congested
	380			18		area over smooth
	200			26		terrain
	740	14-20		0		Farmlands with trees
	560			4		and buildings
	380			11		
	200			16		
Peterson (1963)	1280	5-25	55	20*		Suburban over smooth
	1430		70	20*		terrain NYC
	1370		175	20*		
	1280		575	20*		
Nylund (1968)	80	3	153	11*	10	Suburban NJ
	205	1		36*	25	Manhattan NY
Black and Reudink (1972)	500	1-2	836	27	20	Urban Philadelphia
		2-5		24	30	Suburban Philadelphia

Table 1. Summary of Measured Values - Continued

Reference	ht ft	d mi	f MHz	Median A in dB	10-90% range in db	Description of Area
Barton and Wagner (1974)			455	39		Pittsburgh, rolling
	375	20	862	43		hills with deep valley.
			455	41		and thick tree cover
		10	862	40		
Okumura et al. (1968)	220 m.	5 km	453	24	15	Urban Tokyo
			922	27	17	
			1317	28	18	
			1430	29	19	
Kinase (1969)	220 m	670		40		Central Urban Tokyo
				30		Urban
				25		Suburban
Kirke et al. (1951	220		91	10-12		London, England
Private Communication	25 m		158	9-18		Urban Warsaw
		9-14 km	306	12-21		Suburban Warsaw
			306	10		Small town in Poland
		1-6 km	34	5		Suburban and denser
			46	7		areas in Poland
			171	10		
			306	13		
Private Communication			450-1000	9		Urban areas in SE England

*Attenuation relative to calculated smooth earth. The others are relative to free space.

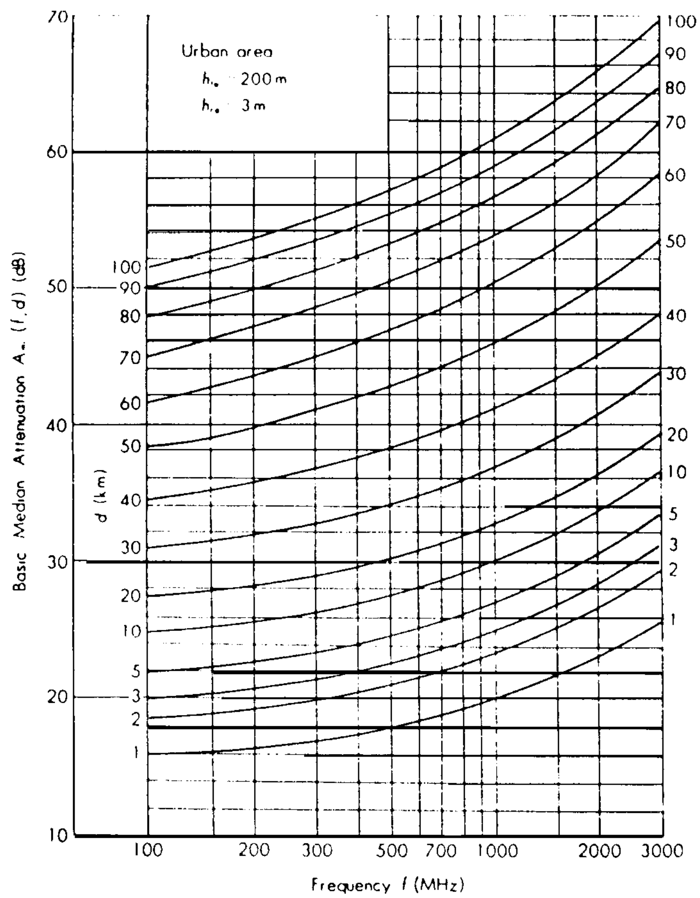

Figure 1. Prediction curve for basic median attenuation relative to free space in urban area over quasi-smooth terrain, referred to h_{te} = 200 m, h_{re} = 3 m. From Okumura et al. (1968).

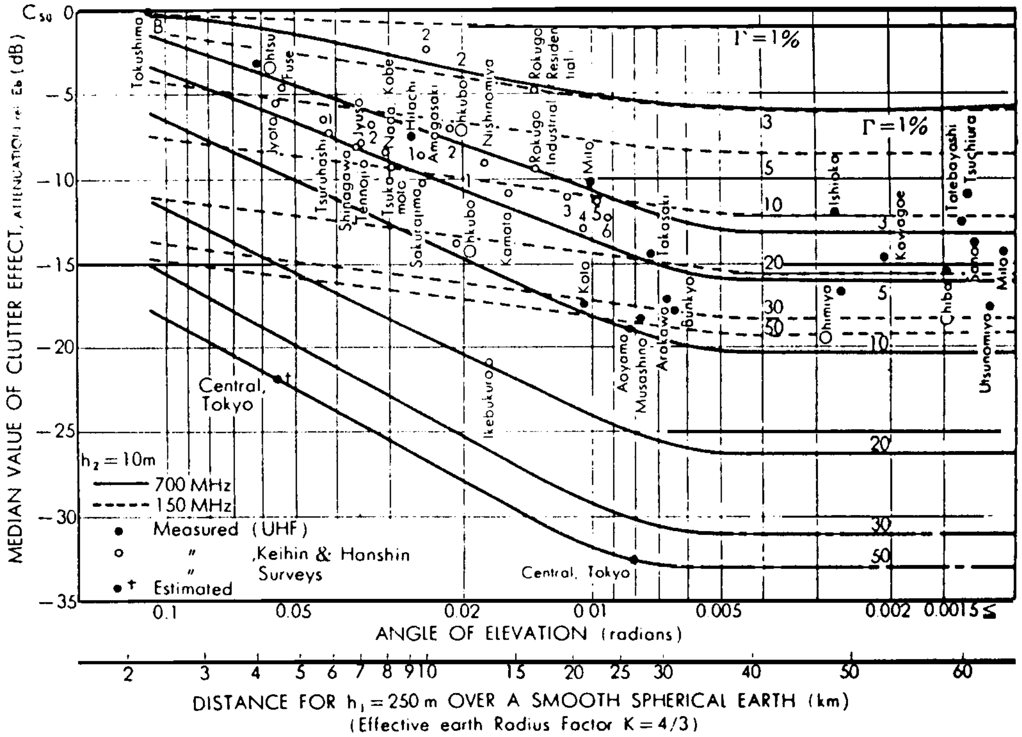

Figure 2. Median value of environmental clutter effect as a function of angle of elevation. From Kinase (1969).

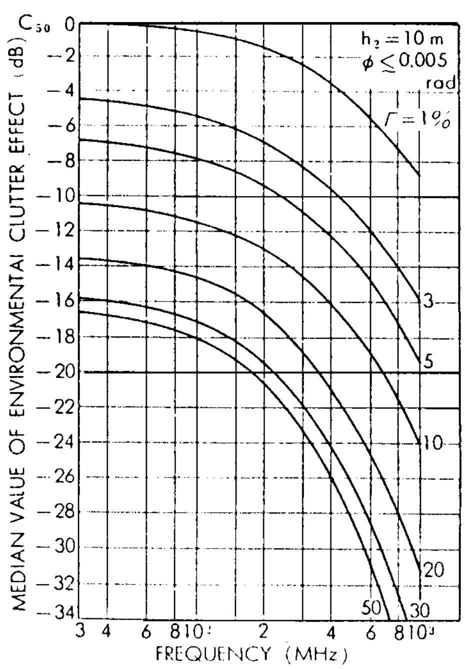

Figure 3. Median value of clutter effect as a function of frequency. From Kinase (1969).

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